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Edited by:

Aleksei L.
All-Russian Institute of Science and Technical Information
Moscow, Russia

Alexander Yu. DOLGOBORODOV
Institute of Chemical Physics
Moscow, Russia

Igor Yu. KLIMENKO
High Pressure Center
Institute of Chemical Physics
Moscow, Russia

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E.G. Nikitenko
Ministry of Defence, Moscow

Применение военной силы для достижения политических целей -явление историческое. Во все времена это было связано с насилием, к которой прибегали политики, когда другие невоенные формы и способы не приводили к нужному результату.

Военная сила всегда представляла собой организованное применение вооруженных сил для достижения определенных политических и военных целей в силовом противоборстве. На протяжении тысячелетий военная политика враждующих государств строилась на основе конфронтационного принципа, который обычно требовал много войск и вооружений. За длительный исторический период происходила эволюция форм и способов применения военной силы, многократно менялись их содержание и значимость, однако во все времена главным ее инструментом и движущей силой было оружие. Не изменилось это положение и теперь.

Рассматривая **силовое противоборство как противоречивое единство политики и вооруженного насилия,** вполне логично исходить из того, что для каждой воюющей стороны формула военной силы во все времена представляла собой **сумму двух главных взаимосвязанных, но противоположных по направлению векторов действий:**

воздействие на противника демонстрацией силы или своими средствами поражения (вектор наступательной или ударной составляющей);

защита своих войск и объектов от действий (поражения) средствами противника (вектор оборонительной составляющей).

Однако в целях более глубокого системного анализа роли оружия в силовом противоборстве условно разделим ее

на четыре взаимосвязанных составляющих, которые всегда были и остаются ее непременными элементами:

поражение войск и объектов противника;
защита своих войск и объектов от поражения;
всестороннее обеспечение действий войск сторон;
управление силами и средствами в вооруженной борьбе.

В такой последовательности попытаемся проследить **влияние оружия (вооружений) на формы и способы силового противоборства,** пройдя путь познания из исторического прошлого, через действительность настоящего в ближайшее будущее. Все эти составляющие в комплексе являются содержанием военного насилия и весьма тесно связаны между собой.

Для познания зависимости форм и способов ведения войн и вооруженных конфликтов от имеющегося оружия **необходимо прежде всего исходить из достигнутого уровня экономики и науки, оказывающих наибольшее влияние на развитие вооружения и военной техники.**

Вскрытию этих зависимостей способствует также **познание взаимосвязи между войной и политикой, остающейся, на наш взгляд, неизменной по отношению ко всем войнам и вооруженным конфликтам, имевшим место в длительной истории «доядерного» периода, независимо от уровня развития вооружений.** Если эта взаимосвязь отсутствует, то, видимо, речь идет уже не о войне, не о военном конфликте, а, скорее, об элементарной вооруженной стычке.

•Политика (по Клаузевицу - разум) порождает войну (по Клаузевицу - орудие).

•Политика есть непосредственная причина, военного насилие - следствие.

•Политика есть содержание, а военное насилие — форма.

•Война — это такое общественное явление, политическое содержание которого выступает в форме вооруженного насилия.

•Политика формирует цели войны, а вооруженное насилие выступает как средство их достижения.

•Война есть противоречивое единство политики и вооруженного насилия.

Во всех этих зависимостях, как видно, оружие вообще не упоминается и находится как бы за кадром. Хотя без применения оружия война невозможна, оно не играет самостоятельной роли в достижении целей безъядерной войны. Во всех прошлых и настоящих войнах с применением обычных средств поражения войска, владеющие этим оружием, являются инструментом в руках полководцев, ведущих к достижению оперативных, стратегических и политических целей.

Все войны и военные конфликты, имевшие место уже после первого и пока, к счастью, единственного целенаправленного применения ядерного оружия — атомной бомбардировки городов Японии — Хиросимы и Нагасаки в 1945 году, необходимо рассматривать во взаимной связи с наличием ядерного оружия на планете. Это оружие уже не находится за кадром, а выходит на передний план и в корне меняет саму войну, военное искусство, а главное, разрушает и взаимосвязь между войной и политикой.

•Война с применением ядерного оружия в конечном итоге неизбежно приведет к уничтожению политического строя, породившего ее.

•В войне с применением ядерного оружия форма вооруженной борьбы уничтожает ее содержание.

•Ядерная война представляется как тотальное вооруженное насилие не только над воюющими сторонами, но и над остальным непричастным к ней человечеством.

•В ядерной войне вооруженное насилие перестает быть средством достижения политических целей.

Как форма вооруженного насилия любая война имеет свою относительную самостоятельность, свою внутреннюю логику развития. Она оказывает влияние на все стороны общественной жизни государств, принимающих в ней участие, вызывает существенные изменения в политике, экономике, духовной жизни людей, влияет на экологические и демографические процессы не только воюющих, но и ряда других государств, даже не имеющих непосредственного отношения к войне. Причем это влияние

сохраняется как в ходе самой войны, так и после ее окончания в виде последствий.

Системный анализ истории «доядерного» периода войн

Применение военной силы, силовой политики во все времена вызывало неоднозначное понимание этого процесса как среди ее сторонников, так и среди ее противников. Из международной практики видно, что вооруженное насилие осуществлялось с различными целями. В большинстве случаев эти цели достигались агрессивным путем и имели захватнический характер. Однако в истории имели место и другие цели применения вооруженных сил — восстановление справедливости, наказание агрессора и др.

Системный анализ истории войн показывает, что в «доядерный» период чередование войны и мира на Земле было естественным и даже в какой-то мере, привычным состоянием. Войны практически никогда не прекращались, имели свое развитие и с древнейших времен до наших дней уже прошло, по крайней мере, четыре поколения войн и военных конфликтов. Основные рубежи смены таких поколений совпадают, главным образом, с историческими качественными скачками в развитии экономики, которые приводили к появлению новых вооружений, а это приводило к смене форм и способов вооруженного насилия.

Вместе с тем, исторический опыт убеждает, что любая война, подготовка к ней и особенно ликвидация ее последствий в большинстве своем возвращали воевавшую страну на более низкую ступень развития.

История свидетельствует, что по крайней мере **четыре прошедших поколения войн относятся к «доядерному» периоду** и все они были инструментом политики, ее продолжением силовым способом. Уже более 50-ти лет мы живем в готовности вести войну пятого поколения — а это ядерная война, и она, вполне понятно, может быть последней в этой эволюции в случае ее развязывания. Такая война неминуемо вышла бы за рамки породившей ее политики и

привела бы к концу всякой политики и к катастрофическим последствиям на нашей планете.

В историческом плане войны первого поколения (древние войны) еще не носили ярко выраженного политического характера. Их следует отнести к рабовладельческому и феодальному периодам обществ с присущим им слабым развитием производства. Вооруженное насилие осуществлялось главным образом с целью взаимного уничтожения противоборствующих войск, состоящих из пехоты и конницы и оснащенных лишь холодным оружием. Победители завладевали всем, что представлялось им ценным, а побежденных, как правило, уничтожали или превращали в рабов.

На определенном этапе истории, связанном с ростом производительности труда, возникновением частной собственности, классов, вооруженное насилие перестало быть просто уничтожением. Оно воплощало в себе как бы единство уничтожения и принуждения и **стало приобретать более выражено политический характер.** Уже войны первого поколения, несмотря на примитивность используемых вооружений, способов их подготовки и ведения, были чуждым человеческой природе средством осуществления политики господствующих классов. Уничтожение человека человеком носило характер естественной необходимости. Более двух тысяч лет человечество существовало на идее Гераклита о том, что война — творец, начало всех вещей, а Аристотель считал войну нормальным средством для приобретения собственности. Видимо, эти доводы и были положены в основу того, что войны приобрели регулярную устойчивую функцию народной жизни, хотя трудно согласиться с подобными доводами как относительно исторических времен, так и в наше время.

Тем не менее, в истории был и такой период, когда еще не было классов, а, значит, войны в тот период не могли быть продолжением политики. Это было элементарное насилие в виде стычек с холодным оружием в предклассовый период, но именно оно уже в первобытнообщинном строе и стало предпосылкой войн первого поколения.

Формы и способы ведения войн второго поколения обусловлены результатом развития материального

производства, появлением пороха и гладкоствольного оружия.

Нарезное стрелковое оружие и нарезная артиллерия, обладающие большей дальностью, скорострельностью и точностью, привели к появлению войн третьего поколения.

Принятие на вооружение автоматического оружия, танков, боевых самолетов, появление новых мощных транспортных средств и технических средств связи повлияли на становление и дальнейшее развитие и ныне не прекращающихся войн четвертого поколения.

Анализируя опыт локальных войн и вооруженных конфликтов, имевших место только за последние 50 лет, можно обнаружить смену закономерности в развитии вооружений: плавный, постепенный эволюционный процесс разработки и модернизации известных видов вооружений начал уступать место скачкообразному их обновлению. Особенно это нашло свое выражение в том, что в этот период появилось не просто новое оружие, а целые боевые системы, способные выполнять те задачи, которые ранее возлагались в основном на живую силу.

Например, в войне в Корее (1950-1953 гг.) было применено 9 ранее неизвестных видов оружия. В войне во Вьетнаме (1964-1975 гг.) таких видов было уже 25. В войнах и конфликтах на Ближнем Востоке (1967, 1973, 1982, 1986 гг.) — около 30. А в войне в зоне Персидского залива (1991 г.) — свыше 100. Безусловно, появление новых видов оружия приводило лишь к изменению форм и способов вооруженной борьбы, но, как правило, не меняло саму войну, и она не выходила за рамки четвертого поколения.

Продолжением научно-технической революции последних 40-50 лет в военном деле явилось ракетно-ядерное оружие, ставшее базой войн пятого поколения, которые, как уже отмечалось, за исключением атомной бомбардировки двух городов Японии в конце Второй Мировой войны в 1945 году, к счастью, еще не возникали. Характерной особенностью развития военного искусства в этот ядерный период явилось снижение интереса к обычному оружию особенно оперативно-стратегического назначения. В период, когда ставка делалась лишь на ядерное оружие, оно перестало играть свою роль. Наступил достаточно

длительный период застоя в развитии обычных высокоточных систем наведения на большие дальности, и вообще в создании дальнобойных средств поражения, способных точно поражать цели обычным оружием. Для ядерного оружия высокой точности не требовалось.

Следует подчеркнуть, что в войнах всех «доядерных» поколений главным объектом поражения непременно были вооруженные силы противоборствующих сторон, т.к. только после их разгрома и полного уничтожения можно было оккупировать территорию, разрушить экономику, свергнуть политический строй противника и добиться победы. В виду того, что обычных средств массированного воздействия одновременно по всей территории, военным и гражданским объектам не существовало, то для достижения крупных результатов приходилось вести длительные наступательные операции оперативно-стратегического масштаба главным образом сухопутными группировками.

Таким образом, во всех поколениях войн «доядерного» периода эти задачи как правило решались лишь в ходе оккупации территории противника и ценой огромных потерь живой силы.

Силовое противоборство в ракетно-ядерный век

В ракетно-ядерный век все резко изменилось и первоочередными объектами поражения могут стать не только вооруженные силы, но и практически вся территория и все население воюющих сторон одновременно, а точнее — **ареной военных действий в ракетно-ядерной войне становится вся планета Земля, ее океанские и морские акватории, воздушно-космическое пространство.**

В силу того, что ядерная война стала вообще невозможной, то именно она и дала на долгие годы жизнь "холодной войне". Сейчас, после ее окончания, предпринимаются попытки найти выход из тупиковой ситуации, в которой оказалось накопленное в огромных количествах ядерное оружие. Стремление раздвинуть завесу вооруженного насилия будущего является непростой задачей. Это связано с кардинальными переменами в военном

планировании, военном искусстве и военном строительстве, и здесь недопустимы никакие просчеты.

Если в прошлых войнах доядерного периода даже крупные просчеты в военном планировании можно было исправить на поле боя и безусловно, только кровью, и причем немалой, то в вооруженной борьбе будущего это исключено, т.к. может быть связано с проигрышем войны в целом. Сейчас, когда идет создание Вооруженных Сил России, когда разрабатываются долгосрочные военно-технические программы, особенно ценным является прогностическое видение войн будущего, скажем, через 15-20 и больше лет. Это необходимо знать уже сегодня, т.к. именно сегодня следует закладывать в производство и будущее оружие и создавать такие Вооруженные Силы РФ, которые будут способны вести вооруженную борьбу и войны будущего.

В этой связи военная теория разрабатывает и исследует, а военная практика проверяет концепции войн шестого поколения, в которых решающая роль отводится уже не живой силе, не ядерному, а высокоточному обычному оружию и оружию на **новых физических принципах. Эти виды оружия примерно через 15-20 лет, вполне вероятно, вытеснят нынешние многочисленные общевойсковые формирования и окончательно сделают ненужным ядерное оружие, во всяком случае, разрушат тот условный барьер, которым длительное время разделялось ядерное и обычное оружие**.

Создаваемые на основе достижений современной науки обычные высокоточные средства по своим поражающим возможностям уже сейчас приближаются к ядерному оружию, но обладают весьма ценным преимуществом — отсутствием экологических последствий после его применения, что полностью меняет характер возможных войн и военных конфликтов. **Войны шестого поколения скорее всего не будут носить длительный затяжной характер, и весь процесс вооруженной борьбы будет протекать скоротечно, по законам и правилам, которые будут**

навязаны сильнейшим — тем, кто в наибольшей степени подготовился к таким войнам.

Но до тех пор, пока будет сохраняться и ядерное оружие, эти новые виды обычного высокоточного оружия в современных войнах и конфликтах будут способны нанести поражение ядерным силам и средствам, а также гражданским объектам атомной энергетики сторон, что, в свою очередь, может стать детонатором и ядерной войны или ядерного поражения типа чернобыльского. Кроме ядерной гражданской технологии в наиболее развитых странах имеются технологии и системы, связанные с высоким риском, обладающие экологическим и социальным потенциалом катастроф. **В случае войны с участием таких государств воюющие стороны вряд ли будут сдерживать себя от нанесения высокоточных ударов по тем объектам, которые и могут стать источником не только большой разрушительной силы, но и заражения радиоактивными и химическими веществами в концентрациях, намного превышающих допустимые для человека нормы.** Уязвимость высокоразвитых стран в случае даже войны с применением обычных средств поражения является объективной действительностью. Они не могут быть жизнедеятельными в условиях любой войны. Сейчас практически все развитые индустриальные страны могут функционировать только в условиях мира. Никакие вооруженные силы и созданная ими оборона не в состоянии обеспечить жизнеспособность этих стран в условиях войны.

Объективно существует ситуация, когда при наличии ядерного оружия, ядерных и химических объектов экономики даже обычная война любого масштаба может стать причиной ядерного или иного катастрофического поражения человечества и потому также становится неприемлемой как инструмент продолжения политики военными средствами. И если такая война все же начнется, то в ходе ее сторона, имеющая на вооружении высокоточное оружие, непременно будет наносить удары прежде всего по важнейшим ключевым объектам на всей территории противника, т.к. только таким путем она быстро и эффективно добьется стратегических результатов.

В случае, если воюющие стороны будут способны вести войны разных поколений, то сторона, ведущая войну шестого поколения, свой первый массированный удар высокоточными средствами очевидно нанесет по войскам и средствам ответного удара противника, а затем ударам подвергнутся и другие объекты и цели на его территории. Уничтожение вооруженных сил противника, созданных для ведения прошлой войны, останется для страны, сделавшей ставку на высокоточное оружие, конечной стратегической целью войны. Другая сторона, не готовая к такой войне, будет вынуждена действовать старым способом и ей ничего не останется, как перейти своими многочисленными сухопутными войсками к обороне и нести значительные потери, хотя при этом ей

может и не противостоять сухопутный противник. Она будет безуспешно пытаться делать ставку на совместные действия различных видов вооруженных сил и родов войск и постоянно ожидать благоприятного момента, чтобы применить свои стратегические средства, будет ожидать возможности ведения воздушно-наземных, воздушных и морских боев, сражений, операций, нанесения огневых и электронных ударов по наземным группировкам противника, высадки своих аэромобильных частей в глубину расположения противника. Однако такого хода вооруженной войны вообще может не быть.

Если проанализировать ситуацию более глубоко, то в это время вооруженные силы любого государства, не готовые к ведению войн нового поколения, вынуждены будут лишь отражать со всех направлений огромный по масштабом и длительности массированный удар высокоточных средств поражения противника, проводимый одновременно с его операцией РЭБ.

Именно в этот период войны сторона, сделавшая ставку на ее прошлый вариант, терпя катастрофические поражения, может прибегнуть к применению ядерного оружия, если оно у нее имеется. Сторона, ведущая войну шестого поколения, не будет стремиться захватить территорию другой стороны и тем более удерживать ее длительное время.

Для государства не подготовленного к ведению войн шестого поколения это будет равносильно поражению, т.к. для противостояния удару воздушно-космических средств надо было иметь совершенно другие вооруженные силы. Они должны были создаваться на базе крупных сухопутных группировок войск, а прежде всего на базе эффективной стратегической системы воздушно-космической обороны, способной отражать длительные массированные удары высокоточных средств противника и на базе достаточного количества высокоточных средств поражения различной дальности действия и средств на новых физических принципах, действующих в соответствии с законами войн шестого поколения.

Те средства отражения и поражения, которые имеются в вооруженные силах на базе сухопутных войск сейчас могли быть достаточно эффективными в войнах четвертого поколения, но практически непригодны в войнах шестого поколения. Не окажет своего влияния и наличие ядерного оружия на достижение политических и стратегических целей в таких войнах. Его применять нельзя даже в минимальном количестве и оно будет оставаться лишь свидетелем поражения ядерного государства в обычных войнах будущего.

Вся длительная история войн показывает, что вооруженное насилие, как неизбежный инструмент войн или военных конфликтов, всегда менялось лишь в сторону увеличения потерь войск, населения, разрушения экономики, нарушения экологического равновесия в природе и др. Тем не менее, войны с применением обычных средств поражения беспрерывно шли в доядерный период, не прекратились в ядерный и, видимо, сохранятся в будущем, не зависимо от того, какое оружие находиться на вооружении государств.

Исторический опыт показывает, что те политические лидеры, которые хотя бы однажды достигли определенных результатов путем применения насилия, идут снова на него без особых раздумий и страха.

Хотя ядерная война на планете невозможна и даже абсурдна, опасность ее возникновения будет сохраняться до тех пор, пока существует ядерное оружие. Но, как уже подчеркивалось, ядерное оружие с момента его появления переросло цели, ради которых создавалось. **Его применение даже в малом количестве в любом военном конфликте преднамеренно или случайно неминуемо приведет ко всеобщей ядерной катастрофе и к гибели цивилизации.** Тем не менее оно реально существует и, видимо, останется на вооружении ряда стран еще достаточно долго.

В современный период наиболее ярко и отчетливо видна гибельность насильственных отношений между людьми. Любая война не может быть средством достижения каких бы то ни было целей. Но, тем не менее, войны, видимо, сохраняться и будущем. Во всяком случае, теория и практика вооруженной борьбы продолжает развиваться.

Научно-технический прогресс и революция в военном деле

На рубеже нынешнего века и тысячелетия в результате революции в военном деле ожидается новый колоссальный скачок в развитии вооружений, а в следствии этого и в формах и способах вооруженной борьбы. Наступает новая эра войн оружия высоких технологий, эра значительного высвобождения человека и вообще живой силы от участия в вооруженной борьбе.

Революция в военном деле — это такие коренные и качественные изменения, происходящие под влиянием научно-технического прогресса в средствах вооруженной борьбы, которые также в корне меняют строительство и

подготовку вооруженных сил, способы ведения войны и военных действий.

Она проявляется прежде всего через стратегию, как составную часть военного искусства. Стратегия охватывает теорию, практику, планирование и ведение стратегических операций и военных действий. Военная стратегия тесно связана с военной доктриной государства и руководствуется ее положениями в решении практических задач. По отношению к другим составным частям военного искусства — оперативному искусству и тактике — стратегия занимает главенствующее положение и является единой для всех видов вооруженных сил. **Если стратегия войны не меняется, а меняется только оперативное искусство или тактика, то это не революция в военном деле, а лишь результаты военно-технического прогресса или научно-технической революции.**

Так, применение военной авиации в войне в Корее привело к изменению борьбы за господство в воздухе, но это не привело к изменению стратегии войны в целом. В войне во Вьетнаме впервые в массовом количестве применялись вертолеты, что привело к изменению общевойскового боя - он приобрел воздушно-наземный характер, но опять же характер войны не изменился. В войнах на ближнем Востоке были проведены экспериментальные поиски высокоточного оружия, однако и здесь характер войны также не менялся. Но вот в войне зоне Персидского залива впервые изменился характер войны в целом, произошла настоящая революция в военном деле.

Для осуществления революции в военном деле требуется совместить достижения военной науки и техники и направить на революционный поворот в стратегии. В мире идет непрерывный процесс военно-технических преобразований в военном деле, и несмотря на то, что в ряде стран он весьма существенен, его результаты пока еще никому не позволяют считать себя в полной готовности к войнам шестого поколения.

В течение многих поколений войн их конечный результат складывался постепенно из совокупности

последовательных боевых действий различного масштаба. В этих действиях принимали участие главным образом противостоящие группировки живой силы. И победитель и побежденный несли большие потери, а формула победы включала: непременный разгром и полное уничтожение вооруженных сил противника, разрушение экономики и свержение его политического строя, что практически всегда требовало оккупации его территории.

С появлением высокоточного оружия в количествах, достаточных для ведения военных действий стратегического масштабы, разгром и уничтожение противника как одна из важнейших целей войны, может достигаться не только путем истребления его средств ответного удара и живой силы (если она применяется в этой войне), но и нанесением ряда последовательных высокоточных огневых ударов по всей глубине его территории, как по его переднему краю, так и по его стратегическим резервам, военно-экономическим объектам, административно-политическим центрам, по пунктам государственного и военного управления.

Высокоточное оружие в силу своих боевых возможностей, даже несмотря на то, что это обычное неядерное оружие, уже превратилось в решающий фактор вооруженной борьбы. Внезапное массированное применение высокоточного оружия может обеспечить решение тех же задач, которые ранее возлагались на ядерное оружие, но теперь уже без опасения радиационного заражения и экологических последствий.

Таким образом, граница между ядерным и обычным оружием будет проходить по задачам, которые одинаково успешно могут решаться либо ядерным, либо обычным высокоточным оружием. Это и позволяет утверждать, что ядерное оружие, а вместе с ним и война пятого поколения, уходят в прошлое, оно перестает оказывать влияние на определение политических и стратегических целей, ему на смену уже идет другое высокоэффективное оружие, у которого нет проблем с применением. Тем более, что поражающие свойства боеприпасов, снаряженных обычным взрывчатым веществом, но повышенного могущества или объемного вз-

рыва, уже сейчас в 30 — 50 раз больше, чем у самых мощных по таким же показателям обычных боеприпасов на базе давно применяемых и уже ставших традиционными тротила, тринитротоллуола и др. На высокоточном оружии будут устанавливаться, как это делается и в настоящее время, и противорадиолокационные устройства самонаведения на источник излучения. В этом оружии найдут применение как новые, так и старые головные части различного назначения: осколочно-фугасного типа, бетонобойные, кассетные, объемно-детонирующие и другие, которые еще будут долго оставаться на вооружении высокоточных средств.

Наряду с увеличением пространственного размаха вооруженной борьбы следует также ожидать значительного повышения точности стрельбы обычными неядерными ракетами различной дальности действия. Если за счет повышения мощности заряда, скажем, в два раза поражающая способность ракеты возрастет на 40 %, то повышение точности также в два раза увеличит ее поражающую способность на 400 %, т.е. в 10 раз. Все ракеты этого класса также станут высокоточными. В целом точность стрельбы всего высокоточного оружия в ближайшие 10 — 15 лет возрастет не менее, чем в 5 раз. Это будет достигнуто главным образом за счет точной навигации каждой летящей ракеты, а также за счет коррекции их полета к цели с помощью специальных устройств на искусственных спутниках Земли.

Война в зоне Персидского залива достаточно убедительно продемонстрировала возможности высокоточного оружия и уже дала мощный толчок в его развитии, что и приведет к существенным изменениям форм и способов вооруженной борьбы.

Известно, что за 20 лет между Первой и Второй Мировыми войнами произошла смена лишь одного поколения средств вооруженной борьбы, и тем не менее Вторая Мировая война по своему характеру уже резко отличалась от Первой Мировой войны. После Второй Мировой войны уже прошло более 50 лет, и за это время

сменилось три-четыре поколения только ракетного оружия, а его дальность, точность, поражающие возможности возросли на насколько порядков, в том числе и в обычном снаряжении.

Высокоточное оружие, которое в своем развитии также уже вышло на уровень четвертого поколения, позволяет, в случае его массированного применения в течение определенного времени, добиться превосходства в войне в целом, а это в корне меняет сам характер войны.

Революция в военном деле и войны шестого поколения

Наиболее развитые государства, принимающие необходимые меры к реконструированию своих вооруженных сил, вполне вероятно будут иметь возможность уже на рубеже первых десяти лет нового века вести войны шестого поколения. Эти войны будут начинаться, продолжаться и завершаться совершенно иначе, чем все предыдущие. **Начинается период, когда будут уходить в прошлое нынешние поколения не только ядерного и обычного оружия, но и вооруженных сил**. Сейчас в наиболее развитых странах идет скрытое, но весьма интенсивное накопление высокоточных средств поражения. Это оружие прошло серьезную апробацию в локальных войнах и вооруженных конфликтах последних десяти лет и становится весьма дефицитным товаром на рынках вооружений. Вполне понятно, что тот, кто завоюет рынок высокоточного оружия сейчас может на этом не только колоссально заработать, но и фактически окупить свои расходы на создание новых вооруженных сил и вооружений.

Безусловно, даже в наиболее развитых странах структура вооруженных сил, формы и способы их применения будут меняться не сразу, а по мере принятия на вооружение достаточного количества этого оружия. **В течение определенного периода времени вооруженные силы таких стран будут постепенно накапливать способность вести войны шестого поколения и сохранят способность выполнять большое количество задач стратегического и оперативно-**

тактического уровня. будут действовать совместно стратегические неядерные средства, воздушные, морские и сухопутные силы и средства доставки высокоточного оружия и оружия на новых физических принципах.

В значительной мере этому будет способствовать также продолжающаяся разработка кроме высокоточных средств и других типов вооружений и в первую очередь оружия направленной передачи энергии, автоматических и автоматизированных систем наведения высокоточного оружия, новых взрывчатых веществ повышенного могущества, средств обработки данных сверхвысокого быстродействия, а также средств радиоэлектронной борьбы.

В войнах шестого поколения найдут широкое применение средства поражения, действие которых по объектам (целям) будет основано на использовании физических форм энергии, а также соответствующих средств защиты от их воздействия. **Можно утверждать, что и в вооруженной борьбе будущего главной останется физическая борьба. Однако вовсе не исключено, что в этой борьбе найдут применение и другие средства поражения.**

Так, если в арсеналах некоторых стран останется на вооружении химическое оружие, то в случае применения таких средств поражения потребуется иметь и применять соответствующие средства защиты от их воздействия. такой вид вооруженной борьбы будет относиться к химической борьбе.

Вид вооруженной борьбы, в котором поражение будет осуществляться биологическим воздействием и будут применяться соответствующие средства защиты, можно назвать биологической борьбой.

Физическая вооруженная борьба — это давно известный вид борьбы, который использует преимущественно физические формы энергии для поражения противника и защиты от физического поражения противника своих войск, оружия, военной техники, объектов и Среды. Для физического поражения в вооруженной борьбе будущего найдет широкое применение энергия всех уже достаточно известных физических форм движения материи —

кинетической, акустической, электромагнитной, энергии элементарных частиц, ядерной энергии, тепловой и др.

Таким образом, в зависимости от форм энергии, в вооруженной борьбе будущего для физического поражения в соответствующих вооружениях будут использоваться различные виды кинетического, акустического, электромагнитного, радиационного и теплового видов воздействия. До конца нынешнего века и возможно какой-то период времени после 2000 года кинетическое поражение еще сохранит свою ведущую роль как главный вид поражающего воздействия на объекты, цели. Оно будет осуществляться с помощью доставляемых с высокой точностью независимо от дальности стрельбы, ракетных и артиллерийских боеприпасов и образовавшихся в результате их своевременного подрыва осколков, ударной воздушной волны и кумуляции. Это будут огневые средства ракетного и артиллерийского типа, но повышенной живучести и высокой стойкости к поражающим факторам в полете со стороны противника (в десятки раз выше по сравнению с настоящими).

SESSION "Mechanical Properties of Materials"

Co-Chairmen:

G.Kanel - Institute of Chemical Physics, Chernogolovka, Russia

K.Iyer - US Army Research Office, USA

MECHANICAL PROPERTIES OF SOLID EXPLOSIVES AT INTENSIVE SHOCK LOADS

S.A.Novikov

Russian Federal Nuclear Center-VNIIEF, Arzamas-16, Russia

Many constructions, containing details from solid high explosives (HE) can be subjected to effect of shock loads with different intensities. HEs differ from other structural materials in that they have explosive transitions when exceeding certain critical levels of dynamic loads. In many cases their beginning occurs after cracks formation and HE details destruction.

The paper presents brief description of several techniques for dynamic tests of samples and details from HE, some experimental results. Shock loads were caused by special explosive loading devices, generating pressure pulses with specified parameters.

That is why together with data on kinetics of excitation of explosive transitions the great attention is paid in the paper to comparatively poorly known area of investigation of dynamic strengths of samples and details from solid HE:

with use of up-dated (at explosive loading) method of Split-Hopkinson-bar (SHB) the "stress-strain" (σ-ε) diagrams were obtained at dynamic compression of some solid HE (different "TNT-RDX" alloys, HMX-based HE) in the range of strains velocity ε=200-500 s^{-1} at different temperatures (from -20 to +80 °C);

with use of the developed SHB-based method data were obtained on dynamic crack resistance of solid HE (the stress intensity coefficient K_{Id}). The stress intensity coefficient vs loading velocity was obtained in three HEs at different temperatures;

research of spall strength of five solid explosive formulations (TNT, two RDX-based HEs, two HMX-based HEs) was performed. Values of spall strength were obtained at the stage of destruction process "nucleation" at characteristic time of loading $t=1.5 \cdot 10^{-6}$ s (plate impact against HE sample);

dynamic strength yield vs normal pressure in shock wave (SW) was obtained in four solid HEs (pressure at SW front was to 2.5 GPa) by method of direct recording of basic stresses behind the SW front by manganine gauges;

description of explosive-type facilities for impact testing of large-scale HE-containing constructions is given. Loading was carried out at the active

part of tested object acceleration. Parameters of loading pulse (pressure growth front, duration, pressure decrease) were formed by explosive generators of pressure (EGP) at reliable confinement of explosion products. The deceleration system allows to catch tested constructions for visual observation after that.

The present work was performed under the financial support of the Russian Fund of Fundamental Investigations (project code 97-01-00344).

DEFORMATION AND FRACTURE OF SOLIDS UNDER SHOCK COMPRESSION: STATE OF THE ART AND PERSPECTIVES OF INVESTIGATIONS

G.I.Kanel

High Energy Density Research Center, Moscow, Russia

The shock-wave technique provides a powerful tool for studying material properties at extremes of strain rates. In spite of a quite sufficient general understanding, the data of shock-wave experiments and material models do not agree in details. This disagreement is a reason to suppose that, at least in same cases, the high-rate inelastic deformation and fracture of solids in shock waves and deformation with low or moderately high rate occur with different mechanisms.

It follows from observations of the stress profiles in metals at unloading and reloading of shock-compressed metals [1,2], and at the loading successively by two compression pulses [3,4], that the shock waves have a specific effect on matter which appears in a high mobility of the crystal lattice. Anomalous X-ray diffraction pattern shifts revealed in experiments with f.c.c. metals [5], as well as molecular-dynamics simulations of the shock induced plasticity [6,7], permit to make conclusion that the whole or almost whole plastic strain at shock compression is produced by the partial dislocations and accompanied by formation of large amount of the stacking faults [8]. As a result, the lattice becomes unstable and, due to that, the fast stress relaxation becomes possible. Perhaps, this effect is not so essential for relatively large-scale processes but it may have an essential influence on the decay of short load pulses created by laser irradiation or by microparticle impacts. Another important aspect of the high-strain-rate phenomena is the transition from thermal activation mode to athermal mechanisms of the plastic deformation. Measurements show, that, in contrast to the yield strength at low and moderately high strain rates, the Hugoniot elastic limit does not decrease with increasing temperature. In some cases the Hugoniot elastic limit, as the temperature approaching melt is achieve, becomes even substantially larger than the value at ambient temperature [9,10].

The inelastic deformation of crystal brittle materials, such as ceramics or rocks, in shock waves may occur through a cracking or in a ductile manner.

The cracking under compression is possible if the existing microdiscontinuities modify the stress field by such a way that the tensile stress components appear [11] in a vicinity of the matter nonuniformities. Such possibility is determined by the material properties as well as the relationship between the deviatoric and hydrostatic components of the stress tensor. The experiments with plane shock waves don't provide an enough wide range of stressed states and not always permit to characterize exhaustively the mechanical properties of brittle materials. The shock-wave experiments with cylindrical symmetry are a way to expand the range of available states in the materials tested.

Silicate glasses exhibit a high yield strength at shock compression. When the peak stress exceeds the Hugoniot elastic limit, brittle glasses become ductile that appears in their high spall strength at large peak stresses. Below the HEL, inelastic deformation may occur by cracking. The multiple crack network forms the failure wave [12] that is initiated on the impact surface, as well as on any internal surfaces, and propagates into the stressed body with a subsonic speed. The material behind of the failure front exhibit zero or nearly zero tensile strength while the spall strength of glass ahead of the failure front is as high as at least 6.8 GPa, that exceeds the spall strength of any steels. The failure wave is an example of non-local phenomena in the sense that response of each elementary volume in the body depends not only on the stressed state, but also on whether the failure wave has approached to this point or not.

The very high yield strength of glasses is a result of their amorphous irregular structures. It is supposed that the irreversible densification is responsible for the plastic flow properties of glasses under high pressure. Once the plastic flow started, the stress relaxation reduces the stress concentration at the crack tip and, by this way, stops propagation of cracks. The high spall strength revealed in the stress range above the HEL means that the ductility is preserved even at tension. A distortion of internal interfaces of the two-piece glass targets was observed at the compressive stresses above the HEL. The distortion is a result of localization of deformation which forms blocks bounded by cracks or shear bands. The peak distortion increases with increasing ramping of the compression wave as a result of reduced concentration of activated cracks or shear bands.

The dynamic tensile strength of materials at load duration of microseconds or less is studied by analyzing the spall phenomena. The free-surface velocity measurements demonstrate an athermicuty of the spall strength of metals [10]. A precipitous drop in the spall strength was observed only as temperature approached the melting point. This drop is explained through a local melting as a result of plastic deformation in the vicinity of damage nucleation sites. The recently developed line imaging interferometer technique provides capability to record simultaneously the velocity histories in many points along a line on the sample surface. With this technique, investigations of the relationship between in-granular and inter-granular strength of crystal solids become possible [13].

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RESISTANCE OF METALS TO PLASTIC DEFORMATION AT HIGH-VELOCITY DEFORMATION ($\varepsilon \sim 10^3$ 1/C)

A.B.Glushak, S.A.Novikov

Russia Federal Nuclear Center - VNIIEF, Arzamas-16, Russia

Collision of fine continuous metallic cylinders, having rigid boundary (Tailors method), is an important experimental instrument to study dynamic mechanical properties of materials in the deformation velocity area up to ~ 10^4 1/sec, which is intermediate one between quasi-static tests and deformation in shock waves.

The paper presents test results of steels St.3, St.30ХГСА (hardening RS 35-40), St.30ХГСА (annealing), pure aluminium, aluminium alloy AMg-6, aluminium alloy D-16, copper, U and U +Mo.

The samples out of materials under investigation, having the length of 100 mm and diameter of 20 mm were quietly accelerated, us-

ing the explosive type facilities for materials mechanical tests up to velocities of 100 to 350 m/sec and were decelerated at rigid barriers, made of hardened 30ХГСА steel. The experimental data show the high strength of aluminum alloys in comparison with pure aluminum and how it is affected by the method of 30ХГСА steel thermal treatment. Two-dimensional computations data fit well geometry (final length and shape) of a sample after loading. High hardening of steel St.3 and copper and low hardening of pure aluminium is noted.

MECHANISMS OF STRUCTURE INSTABILITIES AND KINEMATICS OF DYNAMIC STRAINING TITANIUM ALLOYS

N.I. Zhigacheva, Yu.I. Mescheryakov

Institute of the Mechanical Engineering Problems, Saint-Petersburg, Russia

Investigations of structure instability mechanisms in the shock-loaded single and two-phase titanium alloys are performed by using optical and scanning electron microscopy. Pseudo-alpha-alloy VT-20 is a typical representative of single-phase titanium alloys, while VT3-1, VT-6S and VT-16 are two-phase α–β titanium alloys.

These investigations reveal the difference in kinematics of dynamic straining and fracture for different alloys, the kind of kinematic mechanism being sensitively dependent on the strain rate. So, in the VT-20 titanium alloy within the impactor velocity range of 400-490 m/s the rotational kinematic mechanism at the mesolevel is mainly realized, while outside that interval dynamic straining is realized by means of shear banding and nucleation and grow of tensile cracks parallel to the free surface of target. At the same time, just within aforementioned range of impactor velocities spall-strength of VT-20 alloy turns out to be the highest.

For two kinds of titanium alloys, VT-16 and VT-20, microstructure investigations reveal an unusual kind of rotational instability at the mesolevel. Rotational cells represent the screw formations of 7-10 μm in diameter and 15-20 μm length. The rotational cell are united into chains of 30-80 μm length, the separate screw cells turn relative each other by 180° around the common axis of rotational chain. It should be noted that of all the kinds of titanium alloys tested, just VT-16 and VT-20 have the highest spall strength. In the upper boundary of impactor velocity where the spall-strength of VT-20 alloy is markedly decreased the rotational mechanism of fracture transforms into shear banding and cracking. Thus, it can be concluded that rotational kinematic mechanism at the mesolevel provides the more effective dissipation of

shock wave energy as compared to shear banding and cracking and thereby provides a more higher dynamic strength of material.

Microstructure investigations reveal at least three stages of nucleation and grow of screw rotations. Due to heterogeneous character of dynamic straining and failure of structure-nonuniform media which represent the complex-alloyed titanium alloys all the stages, in principle, can be realized within overall velocity range of impactor. However, below impactor velocities of 450 m/s the first and the second stages are mainly realized. These stages can be characterized by the nucleation and grow of narrow cracks around the future rotational cell. Material inside the rotational cell is still not fragmented. With increasing the impactor velocity the second and the third stage begin to realize. Fragmentation of inner structure of rotational cell herein is more distinct and fragmented structure turns out to be incorporated into screw rotational motion .

Lastly, the third stage of developing the screw rotation is characterized by ultimate fragmentation of material inside the cell.

Dynamic straining of heterogeneous media is known to flow under conditions of particle velocity distribution at the mesolevel, which supposes the three-dimensional motion of medium. At the same time, three-dimensional character of mesoparticle motion is necessary but not sufficient condition for the rotation cells nucleation. Particle velocity distribution has been measured in a series of other materials such as ductile steels, aluminum alloys, copper and so on but none screw rotations has been found before. To our opinion, the second condition for developing the structure instability is thought to be the presence of shock-induced reverse $\omega \rightarrow \alpha$ phase transition in the titanium alloys. This transition transforms the material into structure-unstable state and thereby decreases the threshold for nucleation of rotations. At the same time, the tests of titanium alloys reveal the monotonous increasing of the reverse phase transition threshold with the increasing of the impact velocity, so that the conditions for nucleation of screw rotations gradually disappear. That is why rotational kinematic mechanism transforms back into shear banding and cracking resulting in decrease of the spall-strength of titanium alloys.

As a result it can be concluded that adequate theoretical model for description on of dynamic fracture of titanium alloys should include a self-consistent change of kinematic mechanism of deformation and fracture depending on the strain rate.

INVESTIGATIONS OF THE DYNAMIC STRENGTH VARIATIONS IN METALS.

S.V.Razorenov, G.I.Kanel, A.V.Utkin, K.Baumung*, D.Rusch*, J.Singer*

Institute of Problems of Chemical Physics, Chernogolovka, Russia,
**Forschungszentrum Karlsruhe, Karlsruhe, Germany*

The line-imaging laser Doppler interferometer [1] has been developed to study non-plane motions at the shock-wave loading of condensed matter. With this technique, uniformity of strength properties of materials was studied at the load duration of ~10^{-7} sec or less by recording and analysis of the free surface velocity profiles. An ion beam facility "KALIF" [2] was used to create shock load pulses of small duration in the samples. More or less notable oscillations of spall strength values have been recorded in such different materials as the coarse-grain cast magnesium and molybdenum single crystals.

In the case of magnesium, the strength variations are governed by boundaries of grains. Distribution of the spall strength value along this line is shown in Figure 1. . This diagram indicates that the spall strength is changing from point to point in the sample, but despite of the grain boundary in the ORVIS field of view, there is not any sharp jump in the strength distribution.

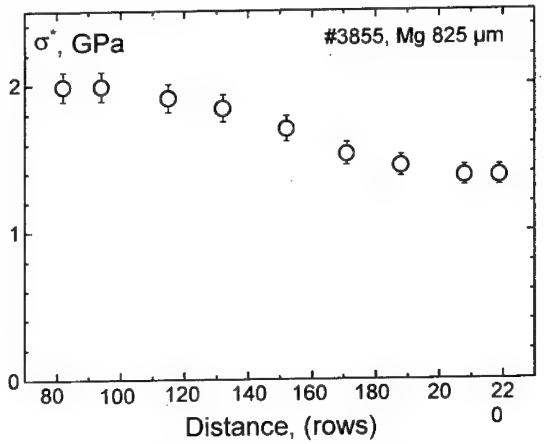

Figure 1.The spall strength distribution in magnesium calculated from free-surface velocity profiles.

In the single crystals, small reductions of the spall strength magnitude were accompanied with decreasing acceleration of the fracture process. This

phenomenon was qualitatively explained in terms of activation of fracture on relatively non-numerous larger defects which are occasionally distributed in the material.

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DYNAMIC PROPERTIES OF URANIUM AT UNIAXIAL COMPRESSION, TENSION AND TEMPERATURES OF 20-600 °C

S.A.Novikov, V.A.Pushkov, V.A.Sinitsyn, B.L.Glushak, O.N.Ignatova

Russian Federal Nuclear Center - VNIIEF, Arzamas-16, Russia

The paper presents results, obtained by dynamic diagrams of uniaxial compression, tension of uranium-238 and its alloy with molybdenum at strains velocities of 200-1800 s^{-1} and temperatures of 20-600 °C. The split-Hopkinson-bar technique was used for the tests. The explosive method of loading was used for dynamic deformation of a sample. In the tests at the elevated temperatures the samples heating was performed by electric furnace with the heating velocity of 1 °C/s. The σ-ε diagrams were obtained. Values of yield strengths and dependences of yield strength on strains velocity and temperature were determined. The determining equations, given in the analytical form, were set up:

$\sigma_i = \sigma_i(\varepsilon_i, \dot{\varepsilon}_i, T, P) = Af1(\varepsilon_i)\, f2(\dot{\varepsilon}_i)\, f3(\varepsilon_i)\, f4(\varepsilon_i)$

Several examples of obtained experimental results and their description with use of determining equation are presented in Tabl. 1,2 and Fig. 1.

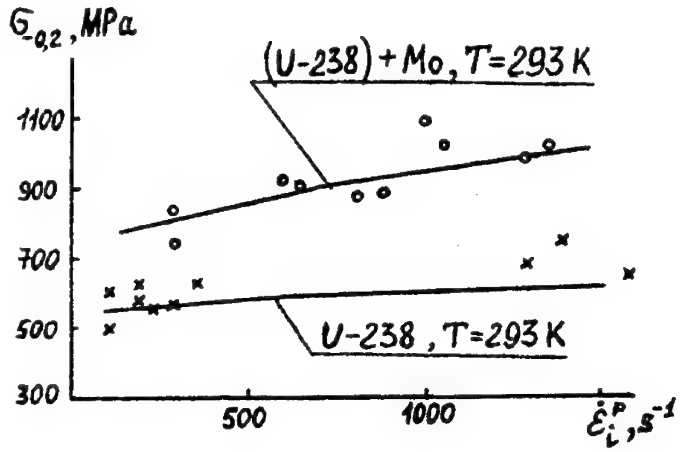

Fig.1. Conditional yield limit; o, x - experimental points,

--- - calculation using model

Table 1

Conditional yield limit of U-238 under dynamic compression

T,°C	ε_i', 1/s	σ_{-02}, Mpa^{exp}	σ_{-02}, Mpa^{calc}
20	100-420	565±42	531-552
	1300-1600	660±80	580-586
100	520-1040	446±48	496-510
200	160-1440	440±30	416-453
400	540-890	300±13	328-334

Table 2

Conditional yield limit of U-238+Mo under dynamic compression

T,°C	ε_i', 1/s	σ_{-02}, MPa^{exp}	σ_{-02}, Mpa^{calc}
20	600-800	868±54	871-900
	1000-1400	990±70	924-965
200	1300-1800	720±67	670-700
400	800-1000	426±52	420-432
600	850-1000	332	300-404

The present work was performed under the financial support of the Russian Fund of Fundamental Investigations (project code 97-01-00344).

SHOCK-INDUCED α–ω PHASE TRANSITION AND KINEMATIC MICROMECHANISMS OF DYNAMIC FRACTURE OF THE SHOCK LOADED TITANIUM ALLOYS

Yu.I.Mescheryakov, A.K.Divakov, N.I.Zhigacheva, Yu.A.Petrov

Institute of Mechanical Engineering Problems, Saint-Petersburg, Russia

A studying of the shock-induced phase transitions and spallation in the single- and two-phase titanium alloys VT3-1, VT-6, VT-16 and VT-20 has been performed by using the interferometric free surface velocity measurements and post-shocked SEM-investigations of microstructure state. Titanium alloys reveal a non-monotonous behavior of spall-strength value within im-

pact velocity range of 270-560 m/s. Under impact velocities between 400 m/s and 490 m/s spall-strength appears to be maximum. In accordance with the microstructure investigations just that interval of impact velocities corresponds to rotational (vortex) kinematic mechanism of dynamic fracture while outside that interval the main kinematic mechanisms turns out to be the shear banding and nucleation and grow of tensile cracks. SEM- investigations of post shocked targets show that rotational cells represent the screw vortex formations of 7-10 μm in diameter and 15-20 μm length. Separate screw rotations are united into chains of 60-100 μm length. SEM-patterns of these chains testify that every next screw rotation turns relative previous by 180°. The screw rotational cells as a rule are linked with the fine cracks of 2-5 μm thick and 15-20 μm length. Their density is maximum within impact velocity interval of 400- 490 m/s.

At least three stages of the screw rotation formation can be identified. Due to heterogeneous character of dynamic deformation and fracture all three stages are, in principle, developed within overall range of impact velocities. However, under impact velocities of 450 m/s the first and the second are mainly realized. These stages are characterized by nucleation of crack around the future screw rotation cell, so that the material inside the future rotation cell is not fragmented. With increasing the impact velocity the second and the third stages begin to dominate. Fragmentation of inner structure herein is more distinctive. Fragmented structure of rotation cell itself incorporated into screw rotation motion. Lastly, the third stage of development of the screw rotation is characterized by the ultimate fragmentation and total screw motion of fragmented material around common longitudinal axis of the rotation cell.

Shock tests has also revealed the direct $\alpha \rightarrow \omega$ and reverse $\omega \rightarrow \alpha$ phase transitions during the direct and release stages of compressive pulse respectively. In the VT-6S titanium alloy the threshold for direct $\alpha \rightarrow \omega$ phase transition increases from 2.55 GPa under impact velocity of 233 m/s to 5.46 GPa under velocity of 545 m/s, which coincides with the analogous data obtained in [1] for high-purity titanium. The reverse phase transition is fixed as a series of short drops of the free surface velocity at the back front of compressive pulse ("beard"). The "beard" has not previously been seen on the free surface velocity profiles for any other metals, it is inherent to the titanium alloys only. After "beard" the slope of back front decreases and moment of spallation is delayed whereas the pull-back velocity increases approximately by 30%. Similar behavior of reverse front of compressive pulse at the free surface velocity profile can be seen within the impact velocity range of 300-560 m/s. The value of threshold stress for the release phase transition increases with increasing the strain rate. For example, in VT-6S titanium alloy its value increases from 1.37 GPa to 3.54 GPa when impact velocity increases from 233 m/s to 545 m/s.

A role of reverse $\omega \rightarrow \alpha$ phase transition in spall properties of titanium alloys under investigation is unclear yet. This role may be important in three aspects.

Firstly, it influences on the formation of very unusual conical-cylindrical geometry of spall plate. Similar situation has previously been described by Shockey *et.al.* [2] during the shock tests of steel plates. By mean of two-dimensional simulation which takes into account the possibility for reverse $\varepsilon \rightarrow \alpha$ phase transition during the spallation of steel in posterior paper Bertholf *et al.* [3] proved that multiple compressive shocks and rarefaction shock produce a square stress pulse in the stress-axial position plane, which results in nearly perfect transfer of momentum to the spall zone of target. Simulation shows that under phase transition condition interaction of rarefaction waves results in conical shape of spall zone. Just the same situation occurs in our experiments. All the spall plates have the evident conical shape and this can serve as additional conformation of presence of reverse $\omega \rightarrow \alpha$ phase transition in dynamically loaded titanium alloys.

Secondly, three-dimensional character of the particle velocity dispersion at the mesolevel is thought to be necessary but not sufficient condition for nucleation of the screw rotations within the spall zone. Presence of appreciable value of the particle velocity dispersion has previously been seen in some of the other materials but rotations have not been found out there. Reverse $\omega \rightarrow \alpha$ phase transition in titanium decreases the density of alloy, converts it into unstable state for short time of atomic rebuilding and thereby decreases the stress threshold for the plastic rotation of matter.

Thirdly, with increasing the impact velocity (> 500m/s) threshold for the reverse phase transition gradually increases. Under these conditions nucleation of rotation becomes difficult and their density decreases. In this range of impact velocities the spallation performs mainly by means of nucleation and grow of cracks parallel to the free surface of target. Rotation motion of medium is known to dissipate the shock-wave energy in the more effective manner compared to shear banding or cracking. That is why the dynamic strength of titanium alloys is appreciably decreases when density of screw rotations decreases.

As a result it can be concluded that an adequate modeling of dynamic fracture of titanium alloys should take into account both shock-induced phase transitions and self-consistent change of kinematic micromechanism of dynamic fracture in the strain-rate range.

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SYMMETRY OF CONVERGING EXPLOSION INITIATION AND PATTERN OF STEEL SPECIMEN DESTRIBUTION

B.V. Litvinov, M.A. Lebedev, D.M. Lebedev

Russian Federal Nuclear Center -VNIITF, Chelyabinsk-70, Russia

Authors of the current presentation in previous papers /1-3/ have already considered the influence of symmetry on development and final outcome of explosion as a systematic and unidirectional phenomenon /4/, the initial symmetry of which is set by initiation either in a point, or along the surface by in advance developed initiation system (IS). Not only initial, but also interim and final symmetries of explosion, i.e. symmetry of explosive device effect on environment will depend both on all its other parts interaction and on the IS.

The results of experiments with cubic charge of high-explosive (HE) are covered in the presentation. The charge with composition TNT/RDX 40/60 and density $1.68 \cdot 10^3$ kg/m^3 was made as two parts and had a spherical cavity inside dia. 90mm. A bulk steel specimen made of 30X13 steel also with dia. 90mm was put in this cavity. The specimen was mounted with the orientation of longitudinal filament (parallel to ingot rod axis) perpendicular to the joint (equator) of two parts of cubic charge.

Thus from the set of initially diverging detonation waves (DW), the number of which is equal to that of initiation points, a single rather complicated converging to the center DW was generated with the help of different IS. This detonation wave transforms to similarly complicated shock wave (SW) more closely to the center, the former at convergence to the symmetry center (center of the specimen) changes its configuration and naturally tends to becoming spherical.

In the symmetry center this SW focuses and reflects as SW, diverging along the specimen and along the explosion products. The surface of diverging SW is an inversion of converging one.

The charge was blasted in the air, and synchronous initiation was performed under three different schemes:

- initiation in the center of each facet of the cube;
- initiation along the ribs of the cube with the help of linear detonation wave generator;
- initiation from the facets of the cube in 16 points, uniformly located on each cube facet.

At "HE-specimen" boundary converging DW leaves the traces on the steel in the places of elevated pressure. Actually the grid of tetragons is noticeable on the specimens, generated by the traces of DWs encounter on their surfaces. Both number and the shape of these tetragons correspond to initiation schemes, described above, i.e. this number is equal to six, twelve and 96.

But initial conditions, set as IS, are uniformly revealed also in pressure relief wave (RW), further propagating to the center, as the number and the

shape of fragments, formed at specimen destruction, corresponds to initiation scheme in each experiment. The specimens as a rule were destroyed uniformly, i.e. in the places of DWs encounter and in accordance with initiation schemes.

At initiation in the centers of all the facets all six fragments have tetragonal bottoms, are the most big and therefore the most relevant and demonstrative for visual examination.

At initiation along the cube ribs the bottoms of fragments are rhombic with the angles ~90° and ~120° in the vertexes. Thus four adjacent rhombs meet under the angles 90° under the center of each facet, and three rhombs under angles 120° under each point of charge ribs intersection.

At initiation from cube facets the dimensions of the fragments also decrease compared to the first experiment, and they also have the shape of tetragonal pyramids, but only in the bottom, the vertexes of these pyramids are not directed to the center of the ball.

The observed effect does demonstrate not only the diversity of waves interaction patterns and necessity of further research of phenomenon, but also indicates to possibility of explosion effect control, for instance, at fragmentation of bulk scrap or at technological fragmentation (including pulverization) of different materials.

In several practical applications, for example, at necessity of loaded specimen recovery, the described phenomenon is extremely undesirable and requires special effort for its elimination, that will also be the control of explosion effect.

A demonstrative example of such type of control would be an experiment, similar to one with initiation in the centers of the facets, where an air gap of 5 mm would be additionally formed between HE and a specimen dia. 80 mm. The grid, corresponding to initiation scheme is visible on specimen surface as before. However, the lines of this grid are formed not by the encounter of detonation waves as in the first experiment, but by plastic deformation of specimen surface under effect of explosion products flows, coming to this surface under varying angles, in the places of their encounter. Therefore these lines look not like depressions, but like sharpened prominences, slightly resembling welded seam and as if constricting the elastic ball.

The cavity, formed at pressure relief, having an octahedral shape with the vertexes under initiation points, located also in the octahedron vertexes, also attracts the attention.

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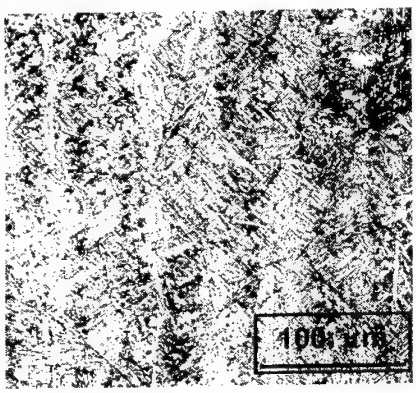
PRESHOCK-INDUCED PHASE TRANSITION IN SPALLED U-0.75WT%TI

A. K. Zurek

Los Alamos National Laboratory, Los Alamos, USA

Uranium-0.75wt%Ti samples were spalled in the range of 5–24 GPa shock pressure. One sample was preshocked to a pressure of 24 GPa, "soft" recovered, and then reloaded and spalled at 10 GPa. The spall strength of U-3/4wt%Ti was found to range from -4.1 to -2.9 GPa when the Romanchenko correction is used in the spall strength calculation. The spall morphology of the sample that was preshocked and then spalled showed a significant change in microstructure from a parent alpha' martensite to a 2-phase eutectoid. The thermodynamically calculated temperature rise resulting from the preshock at 15–24 GPa in these samples is ~555°C. This temperature is not sufficient to induce such a phase change. However, the preshock conditions additionally increase the flow stress of the U-3/4wt%Ti, and it is postulated that this additional hardening is sufficient to increase the temperature above 885°C due to the increased amount of plastic work required during spall, thereby triggering the phase change.



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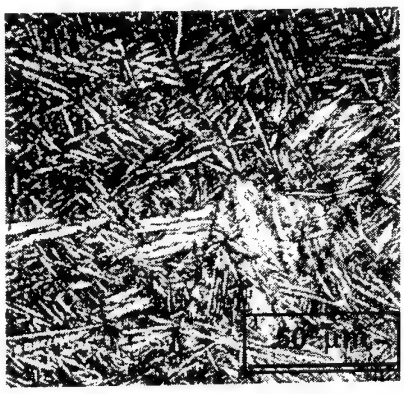

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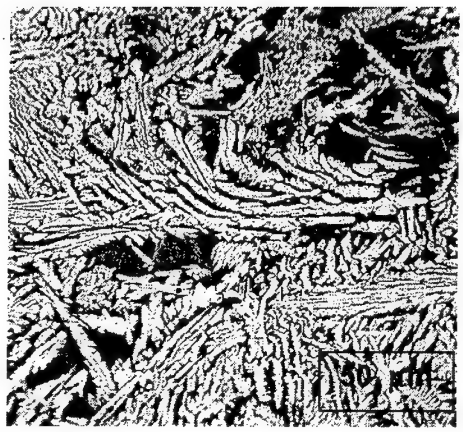

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Figure 1. Optical micrographs showing morphology of material prior to shock loading (a), after a spall test at 10 GPa shock pressure (b), and after preshock at 24 GPa followed by a spall at 10 GPa shock pressure (c).

The microstructure of the spalled depleted U-0.75wt%Ti samples will be presented. The microstructure of the spalled sample preceded by the high strain rate preshock showed eutectoid morphology of $\alpha + U_2Ti$ phase, unlike the samples that were spalled only, which did not change their original α' martensite laths morphology. The spall strengths of depleted U-0.75wt%Ti in a range of 5–24 GPa shock pressure will be listed.

In summary, the spall strength of this alloy decreases with the increasing shock pressure. However, a substantial decrease in spall strength is measured for the preshocked and spalled sample. The predominantly ductile dimple fracture surface morphology was observed in all the samples, with increasing cleavage associated with an increased shock pressure.

QUANTITATIVE DAMAGE EVOLUTION IN TANTALUM UNDER SPALLATION CONDITIONS

W. Richards Thissell, Anna K. Zurek, Jesus M. Rivas, Davis L. Tonks, Robert S. Hixson

Los Alamos National Laboratory, Los Alamos, USA

The three-stage process of nucleation, growth, and coalescence of voids characterize ductile fracture. Considerable energy can be expended in this process prior to the formation of failure surfaces (i.e., a crack). The physics of this process are intrinsically very complex, inherently statistical in nature, and depend markedly upon microstructure, impurity nuances, loading rate, prior loading history, and stress-state. Hence, ductile fracture behavior can be difficult to predict and is the subject of considerable modeling research centered not only at duplicating the behavior of known materials, but also directed towards developing stochastic tools for materials development [1-6].

The stress-state is commonly described in fracture experiments by the degree of stress triaxiality, normalized as the mean hydrostatic stress divided by twice the flow stress, $-P/2\tau$. Pure shear experiments have a stress triaxiality of zero. Uniaxial tension experiments have a stress triaxiality of 1/3 up to the formation of a neck, increasing to about unity at failure after incipient neck formation. Spallation, however, is an experimental condition resulting in very high levels of stress triaxiality, ranging from about 7 to 30. Spallation is an experimental condition resulting from the intersection of two rarefaction waves traveling in opposite directions; hence it is a high strain rate (~10^5 1/s) experiment of controlled pulse duration (~100's ns) [7].

The stress-state of loading profoundly effects the degree and type of plastic flow in the material, the shape of the resulting voids, the porosity at failure surface formation, and the number density and size distribution of voids. Increasing stress triaxialities lead to more uniaxial strain and less uniaxial stress, resulting in less global directional flow yet greater localized directional flow between voids. Increasing stress triaxialities also result in more spherical (smaller aspect ratio) voids in highly ductile materials. Increasing stress triaxialities also cause increasing porosity in the immediate vicinity of the failure surface. Finally, the number density and size distribution of voids also increase with increasing stress triaxiality. Figure 1 shows a micrograph of incipient damage in tantalum under spallation loading conditions.

This paper quantitatively describes the damaged microstructures resulting from recovered incipient spallation experiments performed on two purities of tantalum. The starting materials were annealed *in vacuo* at 1100 °C for one hour and had a mean grain size of 43 and 68 μm for all of the tests. We performed all of the experiments in a gas gun with identical flyer and target geometries, but at varying flyer plate velocities. Hence, the significant variable is the compressive and tensile stress amplitudes among the tests in the same material.

The quantitative analysis combines two-dimensional image analysis with optical profilometry of metallographic sections cut normal to the incipient failure surface [8-10]. The quantified microstructural parameters include void size (true and cross-sectional), position, aspect ratio, void clustering, and void linking. We present statistical analyses of these parameters and describe the effect of stress pulse amplitude on the evolution of these parameters.

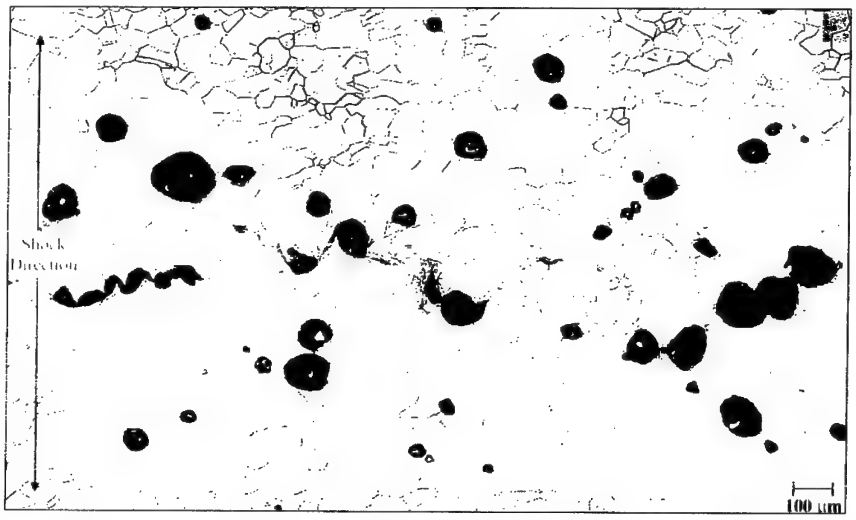

Figure 1: Incipient damage in spalled tantalum showing void clustering, void linking. a wide range of void sizes, and about 25 percent porosity in the plane of maximum porosity.

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FORMATION AND STRUCTURE OF ADIABATIC SHEAR BANDS IN ZIRCONIUM IN SPHERICAL STRESS WAVES

E.A. Kozlov, V.M. El'kin, B.V. Litvinov, A.V. Dobromyslov*, N.I. Talutz*, N.V. Kazantzeva*

*Russian Federal Nuclear Center – VNIITF, Chelyabinsk-70, *Institute of Metals Physics, Ekaterinburg, Russia*

Study into structure of the adiabatic shear bands (ASB) and the peculiarities of their formation in zirconium subjected to the action of spherically converging shock waves of different intensity has been performed. It has been revealed that under the low-intensive mode of loading the ASB occurrence is mainly observed in the layer, ~ 1 mm in thickness, which is found near the plastic fracture cavity being formed in the center of the ball and in the layer ~ 2 mm in thickness which is adjacent to the surface of loading. Under the high-intensive mode of loading ASB is observed in all layers, independently of the layer position depth in the ball, however, their number is greater near the central cavity of plastic fracture. The characteristic features of ASB in zirconium are their propagation in different directions, including those differing from the radial and tangential ones, branching into the more small bands that leads to the tree-like structure, formation of local zones of melting and the availability of the fine internal structure. Such peculiarities of ASB have not been previously observed. The occurrence of the complex structure inside the adiabatic shear bands is associated, perhaps, with the nonhomogeneous localization of the deformation with increasing the band width.

E.A.Kozlov et al., Rep. Russ. Academy Sci., 1998 (in print)

PECULIARITIES OF DEFORMATION AND SPALL FRACTURE OF AUSTENITIC STEEL 60C3G8N8F IN SPHERICAL STRESS WAVES

E.A. Kozlov, G.V. Kovalenko, B.V. Litvinov, A.I. Uvarov,* V.A. Teplov*

*Russian Federal Nuclear Center – VNIITF, Chelyabinsk-70, *Institute of Metals Physics, Ekaterinburg, Russia*

A sphere having 64 mm in diameter and made of austenitic steel 60C3G8N8F was loaded by spherically converging shock waves. Initial pressure on the sphere surface has amounted to 50 GPa, loading impulse duration has been equal to 2 μs. Change in pressure P(R,t) and temperature T(R,t) for a number of Lagrange particles being highly and deeply located along the radius has been evaluated by the numerical modelling method. At the front of the spherically converging shock wave, at the radius of 3 mm, the calculated pressures and temperatures have been estimated to be approximately equal to 190 GPa and 3700 °C, respectively. The loading impulse parameters provided for the compressed and recovered sample are sufficient for the high-strain-rate deformation of material in solid-state in the layers located highly along the radius ($R > 4$-6 mm), for melting at the spherically converging shock wave front at deep radii ($R \leq 3$ mm) as well as for melting the boundaries of grains during unloading in layers at $R \leq 6$ mm. As a result of loading by intensive stress waves, in the sphere material, the numerous defects of microstructure have appeared and in the center the cavity, 8.18 cm^3 in volume and 12.5 mm in radius, has formed. Inside the cavity the rounded central body being insulated from the main mass of the sphere and having diameter being approximately equal to 11 mm - a convergent spall which has formed during the reflection of the second converging shock wave from the cavity boundary has been revealed [1]. The results of investigations performed by the method of optical, scanning and transmission electron microscopy into the compressed and recovered sphere material as well as the peculiarities of the convergent spall material are presented.

[1] E.A.Kozlov et al., Rep. Russ. Acam. Sci., 1998, v. 358, No. 2, pp. 189-192.

LOW OF STRUCTURE AND SOME PROPERTIES CHANGE IN COPPER SPHEREAFTER LOADING BY SPHERICAL WAVES

L.F.Timofeeva, V.M.Filin, V.I.Bulkin, E.A.Klepatskay, V.I.Krivova

Institute of Inorganic Materials, Moscow, Russia

The detail systematically study of the microstructure, the distribution of defects, the density, the microhardness and the microstress change low by copper sphere radius, saved after loading by spherical convergent stress waves under pressure in the sphere center to 200 - 1000 GPa at pulse duration up to 0.5 -1.5ms have been carried out. The manufacture of the sphere, the experiment by shock-wave loading have been done in RFNC -Research Institute of Technical Physic under the leadership of Dr. A.Kozlov.

The results of the study of the sphere material structure and properties after loading have been already published in /1/. Some peculiarities of the close to surface layer microstructure from the side of the central cavity were found : there are gas bubbles, leading to swelling of the areas of metal melted under loading and local gas redistribution might leading to the eutectic type biphase structure formation. Characteristics of point defects, their type and concentration were defined : single vacancies of radius of 0.13 nm predominate, maximum concentration of defects - 30×10^{-7} at.$^{-1}$ is found in the sample located on the sphere periphery. There is proper correlation between material structure and properties change : the material with numerous traces of deformation has the biggest strengthening, microhardness riches of values 110-120 kg/mm^2 on the middle of sphere radius, the level of microstresses is also the highest .

1. E.A.Kozlov, B.V.Litvinov, I.C.Kabin et al. Report in 1991 Topical Conferens of APS on Shock Compressions on Condensed Matter, June 17-21, 1991.

RELIEF OF THE CENTRAL CAVITY SURFACE FORMED IN COPPER SPHERE UNDER LOADING BY SPHERICAL CONVERGENT WAVES OF STRESSES

L.F.Timofeeva, N.I.Nogin

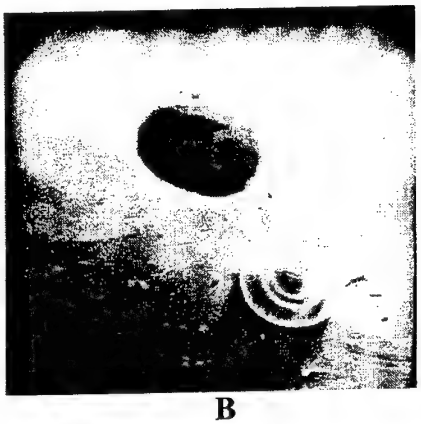
Institute of Inorganic Materials, Moscow, Russia

The results of the surface microctructural study of the central cavity of radius 12 mm, formed in copper sphere of diameter 64 mm in process of loading by spherical convergent waves under pressure in the sphere center to 200 -1000 GPa under pulse duration to 0.5 -1.5 ms. The manufacture of the sphere, the experiment by shock-wave loading have been done in RFNC Research Institute of Technical Physic under the leadership of Dr. E.A.Kozlov . The results of study of the sphere material structure and properties after loading have been already published in /1/ and added in /2/.

The surface of internal cavity has complicated and various relief formed at the account of different shapes and sizes figures growth (Fig.1). They are generally spherical or hemispherical many layers formations connected with surface in point or "by leg" of size from several microns to millimeters, cones and cylinders, finishing by bolls or by" hats", more rarely- by rectangle plates, whiskers in shape of cord or flat tapes. As a rule, around rather big crystals connected with surface there are circle recesses, formed in result of diffusion material withdrawal from surrounding areas to a basis of a growing crystal. Microstructure of them is characterized of elongated recrystallised grains having the eutactical type biphase structure, which is copper - oxigen eutectic.hypothetically. There are numbers of voids in which gas concentration possible throws out some parts of material and in result of it the holes on cavity surface are formed (Fig.2).

It was simulated on base of morphological peculiarities and microstructure analysis,that remarkable part of figures on surface have been formed by diffusion way similar to formations appeared under ion bombardment of material surface under stress condition of surface at temperatures 0.3-0.4 T_{melt} during several hours, but sometimes during many hours /3/. Some peculiarities of the observed relief might be connected with formation of particles by condensation of vapor and their subsequent coagulation /4/. The study of the considered relief leading to modification of surface properties discovers new sides of physic of shock - wave influence on material.

A



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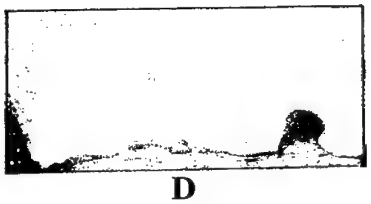

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Fig. 1. Relief of the central cavity surface in copper sphere. Raster-type electron microscope.

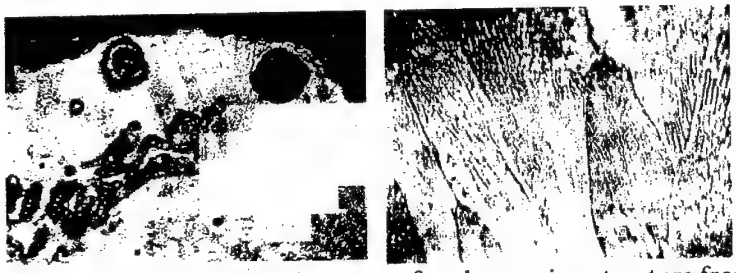

Fig. 2. Microstructure of the close to surface layer microstructure from the side of the central cavity. Optical microscopy.

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DYNAMIC RESPONSE OF PTFE UNDER THE SHOCK LOADING AND RELEASE

S. A. Bordzilovski, and S. M. Karakhanov

Lavrentyev Institute of Hydrodynamics, Novosibirsk, Russia

In the field of studies of mechanical properties and strength of materials it is possible to select a range of stresses from 10 to 100 GPa with the strain rate above 10^4 sec^{-1}, reached by means shock waves. In this range metals were explored sufficiently well and a certain point of view was developed about their shock response. However such class of materials as polymers was insufficiently understood. In contrast with metals they have smaller density, but the main difference is a peculiar internal structure.

The dislocation theory is applied to understand the deformation of metals, but this description does not approach for polymers. On the other hand, it seems rather natural to describe the mechanical relaxation and strength of polymers in terms of Maxwell viscosity [1].

The objective of this work is to receive a useful information about the dynamic behavior of polytetrafluoroethylene (PTFE) under the shock loading and release. The Lagrange analysis was used as a main method to study. In this method the mechanical properties of material are investigated by measuring the evolution of stress – time histories [2]. The analysis of a set of stress histories recorded by embedded manganin gages gave the path of particle in the stress – strain plane.

Experiments were carried out in two variants. In the first one, the samples were loaded by the single stress pulse with the amplitude varied from 16 to 27 GPa with the subsequent release. In these shots the first jump of stress was followed by compression up to maximum amplitude with the rise time ≈ 0.3 μsec. The front structure is typical for

the model based on the Maxwell representation of viscoelastic behavior of a material with a constant relaxation time.

In the second set of experiments the first stress jump ≈ 27 GPa was followed by the reshock raising stress up to 33 GPa and the rarefaction wave. The profile of stress wave was predetermined by the geometry of the loading assembly while evolution depended on the mechanical properties of PTFE. The polymer was characterized by nearly the stationary profile or the reshock pulse. The weak dispersion observed was caused by reducing of sound velocity by 5-10 % along the curve of secondary compression.

Experiments have shown that the loaded PTFE sample at the stress of about 27 GPa behaves like viscous liquid with shear stress of about 0.37 GPa. It was clearly understood when taking into account the loading, reloading and release curves in the stress – strain plane, and absence of the distinctive points corresponding to the beginning of yielding in case of typical elastic-plastic materials. The pathways in the stress – strain plane differed significantly from those for metals investigated earlier by the Lagrange analysis method [3].

The results let us draw to conclusion that at the stresses of several tens GPa and strain rates of more than 10^3 sec^{-1} shock compressed PTFE samples GPa behave like viscous liquid with some pattern of elastic-plastic materials.

As the stress decreases down to ≈ 2.5 GPa the elastic-plastic behaviour prevails, but when the stresses goes up to 27 GPa the viscosity of polymer becomes the dominant mechanism of deformation.

The sound velocity was determined from the slope for both loading and release curves in stress – strain plane. The results show the destruction of the PTFE polymer under shock loading at ≈ 27 GPa.

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СКОРОСТЬ СДВИГА В ЛОКАЛЬНОЙ ОБЛАСТИ ОТКОЛЬНОЙ ЗОНЫ ПРИ УДАРНОМ НАГРУЖЕНИИ МЕТАЛЛОВ

С.А.Атрошенко, Д.М.Оленин

Институт проблем машиноведения РАН, С.Петербург

Исследования проводили на ОЦК и ГЦК металлах. В качестве ОЦК металлов служили перлитные стали: 45 с размером зерна 150 мкм и 30ХН4М с размером зерна 10 мкм, а в качестве ГЦК металла - медь М3 с размером зерна 250 мкм. Ударное нагружение осуществляли с помощью легкогазовой пушки калибра 37 мм. Образцами для исследования служили диски диаметром 52 мм и толщиной 10 мм (ст.45) и 5 мм (ст.30ХН4М и медь М3). При скорости нагружения 200-350 м/с ударником толщиной 1-3 мм в условиях одноосного деформирования был реализован тыльный откол. Для исследования процессов локализации деформации на мезоскопическом уровне использовался метод делительных сеток, нанесенных до ударного нагружения на предварительно отполированные половинки мишени, которые затем соединялись в специальной оправке и подвергались деформированию. Поверхность образца с нанесенной сеткой располагалась вдоль направления распространения ударной волны. Сетка наносилась алмазной пирамидой с помощью прибора ПМТ-3.

Если для исследования квазистатических режимов нагружения метод делительных сеток довольно широко используется, то в условиях ударного нагружения из-за сложности проведения экпериментов с составными мишенями при высокоскоростном деформировании подобные эксперименты с сеткой мезоуровня для оценки поведения внутренних слоев металла являются практически первыми.

В таблице представлены результаты испытаний.

Материал	V,м/с	t,мкс	e,1/c	W,м/с	d,мкм	E,%
сталь 45	212	0,3	1,4.10	100	150	118
сталь 30ХН4М	351	0,7	2,6.10	200	10	82
медь М3	217	0,7	2,1.10	60	250	38

Здесь V - скорость нагружения, t - длительность импульса, e - скорость сдвиговой деформации, W - откольная скорость, d - размер зерна, E - степень деформации.

ПОВЕДЕНИЕ АЛЮМИНИЕВОГО СПЛАВА АМГ-6 ПРИ ДИНАМИЧЕСКОМ НАГРУЖЕНИИ

С.А.Атрошенко, С.А.Новиков*,В.А.Пушков*

Институт проблем машиноведения РАН, С.Петербург.
**Российский федеральный ядерный центр ВНИИЭФ*

Проведено исследование изменения микроструктуры алюминиевого сплава АМг-6 в широком диапазоне скоростей деформации при квазистатическом и ударно-волновом** нагружении. Испытания на динамическое сжатие осуществлялись с использованием составных стержней Гопкинсона при скоростях деформации 200-2000 1/с и методом высокоскоростного соударения пластин в условиях одноосной деформации с помощью пневматической пушки калибра 37 мм в диапазоне скоростей 100000-1000000 1/с. В первом случае образцы представляли собой сплошной цилиндрдиаметром 8 мм и длиной 8 мм. Размеры образцов выбирались из условия минимального влияния радиальных и осевых инерционных сил, а также сил трения. Во втором случае это были диски диаметром 52 мм и толщиной 2 мм.

По результатам испытаний на стержне Гопкинсона был определен предел текучести на динамическое сжатие, а из испытаний по высокоскоростному соударению пластин - откольная скорость. Эти данные представлены в таблице. Как видно, предел текучести с ростом скорости деформации возрастает. Величина откольной скорости во всем исследуемом интервале практически не зависит от скорости деформации.

Скорость нагружения, 1/с	Динамический предел текучести, МПа	Откольная скорость***, м/с
300-500	185	
1200-1300	200	
100000-1000000	120	120

***Данные взяты из работы Ю.И.Мещерякова, А.К.Дивакова, В.Г.Кудряшова. "О динамической прочности при отколе и пробое", ФГВ, 1988, N2, с.126-134.

АМг-6 относится к группе термически неупрочняемых алюминиевых сплавов. Для устранения склонности к окислению этот сплав легирован бериллием, а для исключения укрупнения зерна, вызванного введением бериллия, он модифицирован титаном. Структура сплава АМг-6 представляет собой твердый раствор с включениями интерметаллидных фаз, которые расположены вдоль направления прокатки. Динамическое деформирование инициирует последующее естественное старение этого сплава. Одна из причин этого ускорение диффузионных процессов в динамически деформируемом материале за счет возрастания плотности дислокаций и точечных дефектов.

Динамическое деформирование приводит к интенсификации процессов естественного старения, т.е. к ускорению процессов распада, а также и упрочнению сплава, что и видно из данных, приведенных в таблице - с увеличением скорости деформации прочность растет. Особенно интесивно все эти процессы идут при ударно-волновом нагружении - так называемое "ударное старение" ("shock aging").

**Ударно-волновое нагружение осуществляли Ю.И.Мещеряков и А.К.Диваков.

SESSION "Numerical Modeling of Shock Wave Processes in Metals"

Co-Chairmen:
P.Makarov - Institute of Strength Physics, Tomsk, Russia
R.Armstrong - University of Maryland, USA

DISLOCATION MECHANICS DESCRIPTION OF MECHANICAL PROPERTIES

R.W. Armstrong* and F.J. Zerilli**

**Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, **Indian Head Division - Naval Surface Warfare Center, Indian Head, MD 20640, USA.*

Numerical modeling of the permanent deformation and fracturing behaviors of metals under dynamic loading conditions is facilitated by knowledge of the responsible crystal dislocation mechanisms that operate in a particular lattice structure. Thus, individual dislocation movement in a bcc lattice accounts for a temperature and strain rate dependent yield stress while these influences are in the strain hardening behavior of fcc metals and alloys [1]. Different hcp metals are either bcc or fcc-like. The greater importance for bcc materials of cumulative dislocation interactions in blocked (slip band) pile-ups produces a stronger Hall-Petch dependence of flow stress on the reciprocal square root of polycrystal grain diameter [2], and this dependence connects directly with the corresponding importance of grain size influences on twinning, cleavage fracturing, and adiabatic/shear banding behaviors [3]. The dislocation mechanics framework provides for additional modeling analysis [4] of such processes as dynamic recovery at large strains, discount of potential drag embrittlement at greater strain rates compared with enhanced dislocation generation, influences of grain size and particle size/spacing on ductility, and nanoscale shock hardening considerations [5] relating also to nanocrystalline grain size effects.

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CRITERION FOR CHANGE OF KINEMATIC MECHNISM OF DYNAMIC STRAINING AND FRACTURE AS NOISE-INDUCED PHASE TRANSITION

Yu.I.Mescheryakov

Institute of the Mechanical Engineering Problems, Saint-Petersburg, Russia

Dynamic uniaxial-strain tests of different heterogeneous materials, such as ductile high-strength steels, copper of different purity, aluminum and titanium alloys, show that the shock-wave propagation process should be characterized not only by the time history of the average particle velocity **V(t)** but also by the particle velocity dispersion $<\Delta V^2(t)>$ at the mesoscopic scale level (0.1-10 μm). The evidence of the mesoparticle distribution in the velocity space undoubtedly means that:

(i) their motion is three-dimensional although at the macrolevel one deals with one-dimensional shock wave propagation with the average particle velocity in a continuous medium,

(ii) particle velocity dispersion value can serve as a quantitative measure of relaxation properties of dynamically loaded material.

Analysis of the shock-wave behavior in the heterogeneous media shows also that amplitude of shock wave (i.e. particle velocity **V(t)** at the plateau of compressive pulse) suffers an additional decay whose value sensitively depends on degree of non-stationarity of shock-wave propagation process [1]. Furthermore, the shock wave can suffer an appreciable decay at the first front of compressive pulse but may restore its amplitude at the release front. Physically this means that kinetic energy of flow (average) motion of medium in the shock wave can be transferred to the separate mesoparticles which have differ-

ent velocities because of velocity scattering during the wave propagation in the heterogeneous medium. After relaxation the distributed energy of mesoparticles again returns to the flow motion of medium. On the physical kinetic language, that kind of shock-wave decay proves to be reversible depending on degree of stationarity of the particle velocity distribution function at the mesolevel.

This phenomenon can be used for the coupling between kinetic features of heterogeneous medium and its macroscopic response to be established. Experiments show that the additional decay of the particle velocity appears by the threshold way when velocity dispersion and/or rate of its change achieves a certain threshold value [2]. On the other hand, microstructure investigation of specimens after shock loading revealed an evident presence a numerous cells of mesoscopic scale level, which have been identified as elementary vortex formations, or mesorotations [3]. This allows to conclude that the threshold change of shock-wave amplitude happens due to change of kinematic mechanism of straining at the mesolevel from translational to rotational. In this way the change of kinematic mechanism of dynamic straining is considered to be a noise-induced phase transition, a role of noise intensity plays the particle velocity dispersion. For the purpose of describing that kind of the shock-wave decay (which can be called a "fluctuative" decay) a stochastic approach to shock-wave propagation in the shock compressed heterogeneous medium is proposed where the particle velocity $\mathbf{V}(t)$ is accepted to be consisting of average component and random noise. Deterministic equation describing the system is expressed in terms of time evolution of the particle velocity :

$$d\mathbf{V}(t) / dt = \alpha(t)\, \mathbf{V}(t) - \chi(t)\, \mathbf{V}^2(t) \quad (1)$$

Parameters $\alpha(t)$ and $\chi(t)$ characterize an influence of external conditions, i.e. degree of heterogeneity of medium, on the shock-wave amplitude. The value $1/\alpha$ has a sense of time of macroscopic evolution of considered nonlinear system, while $1/\chi$ is the distance where annihilation of dislocations happens. When parameter α includes a regular parts α_o and noise parts α_1, so that

$$\alpha = \alpha_o + \sigma\, \alpha_1 \quad (2)$$

where σ is the intensity of noise, equation (1) transforms into proper stochastic equation [4]:

$$d\,\mathbf{V} = (\alpha\, \mathbf{V} - \chi\, \mathbf{V}^2)\, dt + \sigma \bullet d\mathbf{W} \quad (3)$$

where $\mathbf{W}$ is the Wiener random process. Solution to appropriate Fokker-Plank equation related to the stochastic equation (3) results in probability density for the state of system while the diffusion coefficients of that equation define the criterion for change of kinematic mechanism of dynamic straining

$$\alpha/2 = d\,\zeta / d\,t \quad (4)$$

Here $\zeta = \Delta\mathbf{V} / \mathbf{V}$ is the so-called variation coefficient in the probability theory, $\Delta\mathbf{V}$ is square root of the particle velocity dispersion and $\mathbf{V}$ is average

particle velocity (mathematical expectation of random value such as particle velocity in heterogeneous medium). Under strain rates where $\alpha/2 << d\zeta / dt$ maximum probability density corresponds to the zero value of the average velocity $V(t) = 0$. In this case the rotational (vortical) kinematic mechanism of deformation is preferably realized. If, however, particle velocity dispersion changes slowly, one faces the opposite situation when $\alpha/2 >> d\zeta /dt$. In this case the translational motion of medium dominates with non-zero average velocity $V(t) \neq 0$ in the wave propagation direction.The theory is compared with real behavior of plastic waves in stainless and ductile high-strength steels measured with the velocity interferometer technique.

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NUMERICAL SIMULATION OF DAMAGE GROWTH IN NATURAL URANIUM AT SPALL FRACTURE

B.L.Glushak, I.R.Trunin, O.A.Uvarova

Russian Federal Nuclear Center-VNIIEF, Arzamas-16, Russia

According to present-day notion the spall fracture is multistage temporal process of growth and cumulation of damage ω with macrocracks formation. To describe regularities and peculiarities of this process, joint analysis of numerical and physical results is used. This allows to construct the most comprehensive and plausible picture of fracture.

In this work the numerical simulation is performed using two-stage microstatistic kinetic model of NAG type with internal parameters [1]. Results of this model application for verification of experimental (i.e. obtained in planar impact tests [2,3]) and model data are presented in tables and graphs. They show good agreement between each other.

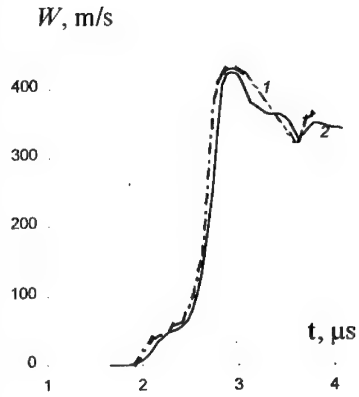

Fig. 1. Sample free surface velocity W vs time.
1 - test, 2 - calculation
(Δ_{imp} = 6.35 mm, Δ_s = 7.5 mm, σ_H=11.8 GPa, impactor - sapphire).

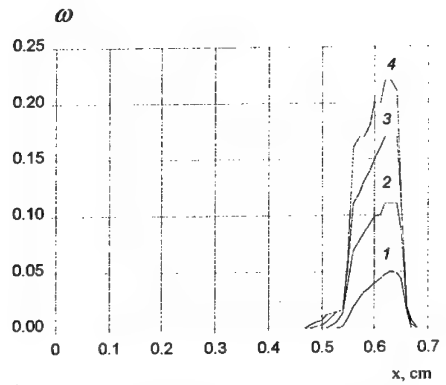

Fig. 3. Distribution of damage ω along sample thickness at different time moments:
1 - 3.4 μs; 2 - 3.6 μs; 3 - 3.8 μs; 4 - 4.0 μs.
Time count - from the impact moment.
(Δ_{imp} =6.35 mm, Δ_s =7.5 mm, σ_H=11.8 GPa, impactor - sapphire).

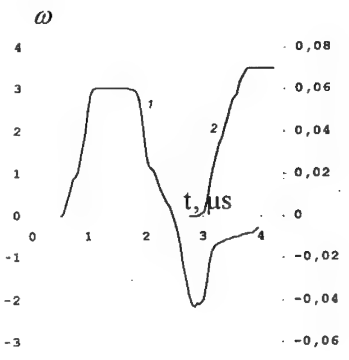

Fig. 2. Stresses σ and damage ω in the fracture zone vs time. 1 - $\sigma(t)$, 2 - $\omega(t)$
(Δ_{imp} = 2 mm, Δ_s = 4 mm, σ_H=3.1 GPa, impactor - uranium).

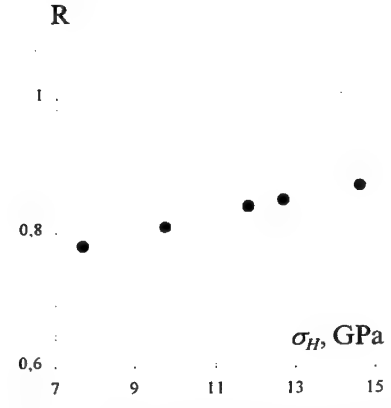

Fig. 4. Parameter R, correlating with damage, vs shock wave amplitude σ_H.
- calculation, • • • - test
(Δ_{imp} = 6.35 mm, Δ_s = 7.5 mm, impactor - sapphire).

The fact that it is possible using the model to carry put adequate description of experimental data, obtained by gauges external regarding to the process under study, allows to turn to numerical research of processes, which occur directly inside material, i.e. to obtain real picture of the damage growth process, impossible by existing experimental research methods.

The performed researches show that micromechanic kinetic model gives adequate description of experimental results of natural uranium behaviour under pulse tensions. Application of this concept will allow to model the damage growth processes in uranium constructions under conditions of loading them by impact of high-velocity plates and detonation wave.

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NUMERICAL SIMULATION OF THE DAMAGE ACCUMULATION PROCESS IN COPPER, RESULTED IN SPALL FRACTURE AT DYNAMIC LOADS

B.L.Glushak, S.V.Koritskaya, I.R.Trunin

Russian Federal Nuclear Center - VNIIEF, Arzamas-16, Russia

Study of behaviour and fracture of materials and elements of constructions, subjected to effect of pulse dynamic loads (force and thermal loads), is an urgent problem of both scientific and applied significance.

The existing experimental methods for study of this problem have the indirect character. Due to this reason they not always have accuracy and reliability when obtaining information on the internal state of a substance in the fracture process. Besides, results, obtained by gauges, external regarding to the object under study, do not answer the question on the material damage extent - the characteristic, which is, in our opinion, one of the important characteristics for spall fracture study.

That is why, the methods for numerical solution of such problems undergo currently increasing development. For this purpose it is necessary to employ physically clear and substantiated models for description of the substance state (determining equations) and the material fracture models. At the same time the model should describe both experimental dependencies (velocity of the free surface of a loaded sample, or change of stress versus time at the sample-base interface boundary) and dependencies, obtained directly by cal-

culations, characterizing the spall fracture process (damage distribution through the sample thickness and identification of the zone with the highest damage extent, stress versus time dependence in the plane of maximum damage extent, etc.).

Construction of models, allowing to describe the above mentioned regularities, is based on the kinetic concept of fracture, when the spall fracture process, proceeding in time, is divided into several stages with different boundaries between the stages or with no boundaries.

In this work the model NAG is used for modeling of the damage accumulation process. This model includes description of two stages of spall fracture: nucleation of microdefects with characteristic size $\mathbf{R}_0$ and their further growth under tensions.

Copper is selected as the material under study, which is characterized by viscous destruction, determined by nucleation and growth of defects, having approximately spherical form.

Besides, copper is one of the most completely researched by experiments as a structural material. This gives opportunity to compare the calculation results and the experimental dependences for three types of dynamic loading: for the case of projectile-target collision, explosive loading, and electrons flow effect on thin foils.

MESH-INDEPENDENT DUCTILE FRACTURE CALCULATIONS.

L. Seaman and D. R. Curran

SRI International, Menlo Park, CA 94025, USA

The purpose of our study was to obtain computed results for damage that are independent of the finite element size being used. We are considering ductile materials, such as copper and aluminum, and are treating damage with a microdamage model in which microvoids are nucleated and grow under tensile loading. The microfracture model contains fracture processes that are dependent on the local stresses and strains; hence, it is clear that these stresses and strains must be mesh-independent before we can hope to have fracture results that are independent of the mesh size. Therefore, we began by determining an appropriate strain-rate-dependent mechanical model that would provide the appropriate shock front thickness. With such a model, and an appropriately chosen mesh size, the computed wave profile should match the observed shock front thickness and not change if the mesh is further refined.

To determine the mechanical model for the rate dependence of the material we used the results of Swegle and Grady [1985] and Dunn and Grady [1985]. The model and parameters they have developed are based on measurements of the apparent shock front thickness in several materials. According to our calculations based on their model, the shock front

thicknesses shown in Figure 1 (in cm or in μs) depend strongly on the compressive stress amplitude. For the 1 to 2 GPa stresses we are considering for plate impacts to cause fracture, the steady state shock front thicknesses are several cm or μs. Therefore, the steady state shock front is not achieved in the tests; the stress waves are all unsteady and the wave fronts are still developing and spreading.

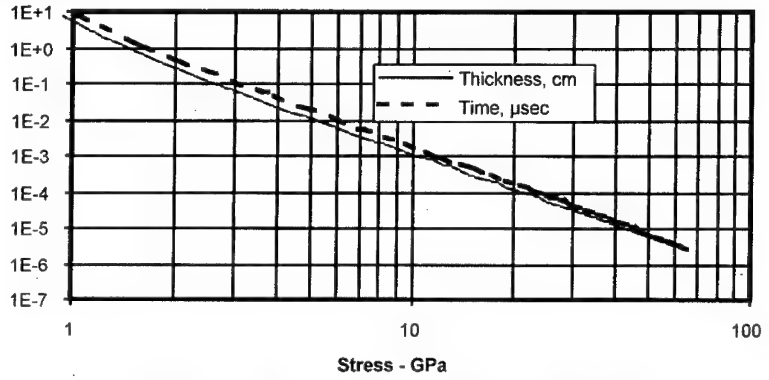

Figure 1 Variation of shock front thickness with stress level

To represent the mechanical behavior of the shock front development with fair precision we incorporated the strain rate dependence of Swegle and Grady into our elastic-plastic model for the deviatoric stresses. This is an extrapolation for their model because their model was actually matched only to the steady state shock front profiles; we are assuming that the model represents the physics well enough that it also can describe the gradual development of the wave front. Because of this unsteadiness of the wave fronts in our case, we cannot estimate the shock front thickness from Figure 1, but must perform a simulation with the model with a fine enough mesh to allow us to compute this thickness. For subsequent calculations, we can then choose a mesh size that is appropriate for this thickness.

The development of their model for the shock front begins with the experimentally obtained relation between the maximum strain rate in the shock front and the jump in stress in the plastic wave:

$$\frac{d\eta}{dt} = A(\Delta\sigma)^4 \qquad (1)$$

where ? is the strain $1 - V/V_e$, V_e is the specific volume at the end of the elastic precursor, A is a material constant [about 6000 $1/(GPa^4\text{-s})$ for aluminum], and ?? is the stress jump from the precursor level to the peak stress of the steady wave. Next they note that the viscous stress in the shock front (shear stress above the yield strength) is proportional to the square of ?? to allow the total stress to follow the Rayleigh line. Then the strain rate is related as follows to this viscous stress:

$$\frac{d\eta}{dt} = A(\Delta\sigma)^4 = A\left(\frac{4C_o^2}{3SV_e}\right)^2 (\bar{\sigma} - Y)^2$$

$$\text{where } (\Delta\sigma)^2 = \frac{4C_o^2}{3SV_e}(\bar{\sigma} - Y) \qquad (2)$$

Here C_o is the plastic wave speed at zero stress, S is the coefficient of the second term in the linear U_s–u_p form for the Hugoniot, $\bar{\sigma}$ is the equivalent stress, and Y is the yield strength. The basic equation for the rate-dependent deviator stress is then given by

$$\frac{d\bar{\sigma}}{dt} = 2G\left[\frac{d\eta}{dt} - \frac{d\eta^p}{dt}\right] = 2G\left[\frac{d\eta}{dt} - A\left(\frac{4C_o^2}{3SV_e}\right)^2 (\bar{\sigma} - Y)^2\right] \qquad (3)$$

where η^p is the plastic strain. Here we are relating the viscous stress to the plastic strain rate, rather than to the total strain rate. At this point we introduce the viscous stress $\bar{\sigma}_v = \bar{\sigma} - Y$, and allow the yield strength to work harden in proportion to the plastic strain with a work-hardening modulus of H. Then Eq. (3) becomes

$$\frac{d\bar{\sigma}_v}{dt} = \frac{d\bar{\sigma}_{v,el}}{dt} - (2G + H)A\left(\frac{4C_o^2}{3SV_e}\right)^2 \bar{\sigma}_v^2$$

$$\text{with } \frac{d\bar{\sigma}_{v,el}}{dt} = 2G\frac{d\eta}{dt} \qquad (4)$$

where the first term on the right is the elastic stress rate. The solution over a time step ?t is

$$\bar{\sigma}_v = a\frac{a + \bar{\sigma}_{vo} - (a - \bar{\sigma}_{vo})\exp(-4ab\,\Delta t)}{a + \bar{\sigma}_{vo} + (a - \bar{\sigma}_{vo})\exp(-4ab\,\Delta t)} \qquad (5)$$

$$\text{where} \quad 2b = (2G + H)A\left(\frac{4C_o^2}{3SV_e}\right)^2$$

$$\text{and} \quad a^2 = \frac{1}{2b}\frac{d\bar{\sigma}_{v,el}}{dt}$$

In a wave propagation computation $\bar{\sigma}_v$ rises parabolically to a peak at mid-height of the wave front, then returns to zero at the top of the wave. This solution for the rate-dependent deviator stress was added to our standard

model for a work-hardening plastic material and combined with the fracture model.

The microfracture model (described by Curran et al 1987) has parameters fitted to a series of plate impacts in 1145 aluminum. The threshold stress for nucleation is 0.3 GPa and the nucleation rate for a stress of 1 GPa is 7.1 ? $10^{20}/m^3/s$. The threshold stress for growth of the voids is 0.48 GPa, decreasing with increasing damage according to the Carroll-Holt model for porous materials[1972]. The growth rate is governed by an apparent viscosity in accordance with the model of Poritsky for bubble growth in a viscous material[1952]. The viscosity for this growth is 21 Pa-s. The analysis of Grady and colleagues referred to above associates this viscosity with a shock front thickness of 60 ns.

We performed a series of plate impact simulations with varying mesh sizes to examine the foregoing analytical results. For the simulations we chose an actual experiment in which a 0.114-cm aluminum plate struck the 0.318-cm-thick target of 1145 aluminum (commercially pure, very soft) at 185.6 m/s and caused an intermediate level of fracture damage in the center of the target. For plate impacts in aluminum with a shock pressure of 1 GPa, the shock front thickness is about 35 ns, the apparent material viscosity is 200 poise (dyn-s/cm^2 or 20 Pa-s), and the relaxation time constant is 0.74 ns. The necessary finite element thickness for the simulation of the stress history was 17 μm. For mesh-independence the damage computations appeared to require a mesh with one-half this size. We used element sizes of 4 to 140 μm in the study.

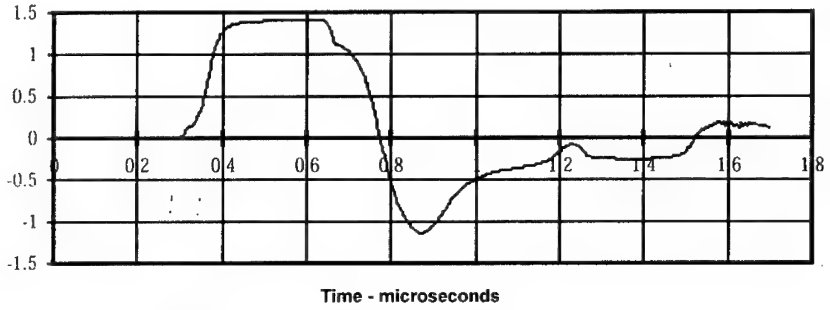

Figure 2 Stress history at the plane of maximum damage for 0.114-cm Al plate impacting 0.318-cm 1145 Al plate at 185.6 m/s (17 μm mesh)

The stress history (at the plane of maximum damage) computed with the mechanical and fracture models in a one-dimensional wave propagation code is shown in Figure 2 for a mesh size of 17 μm. The apparent rise time of the plastic wave is 40 ns. The tensile portion of this history (shown in Figure 3) is given for computations with mesh sizes from 4 μm to 69 μm; the curves for 4, 9, and 17 μm appear to coincide, showing that a mesh-independent stress

history has been achieved for 17 μm and smaller. The tensile stress history also has a rise time of about 40 ns.

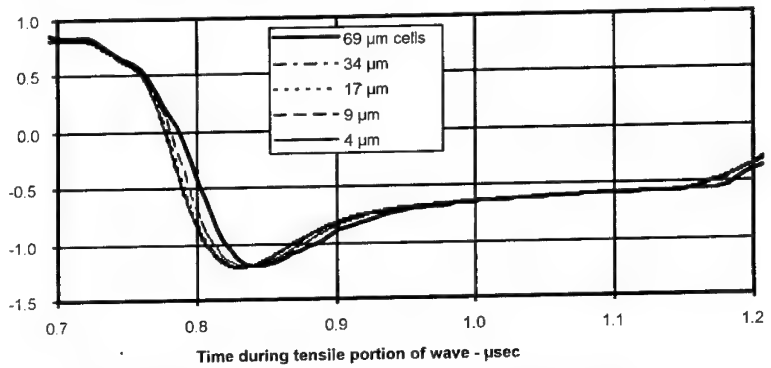

Figure 3 Stress histories in an Al 1145 impact at several cell sizes
Impact #939 at 185.6 m/s, 0.318 cm target

The variation of fracture damage (relative void volume) with distance through the sample and with mesh size is shown in Figure 4. Here there is a continuing increase in peak damage with decreasing mesh size. Figure 5 exhibits the peak damage as a function of mesh size. There is a pleasing smoothness to this result, suggesting that the numerical method is providing stable and reliable values. The curve extrapolates to a void volume of 0.067, just 5 % larger than the value at a mesh size of 17 μm.

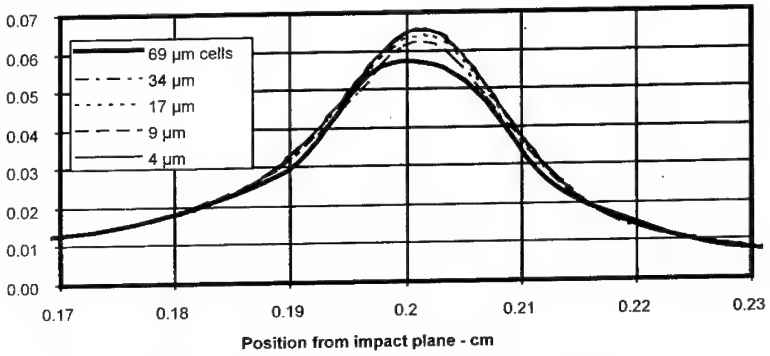

Figure 4 Variation of Damage with Position for various cell sizes
Impact in AL 1145 at 185.6 m/s, 0.318 cm target

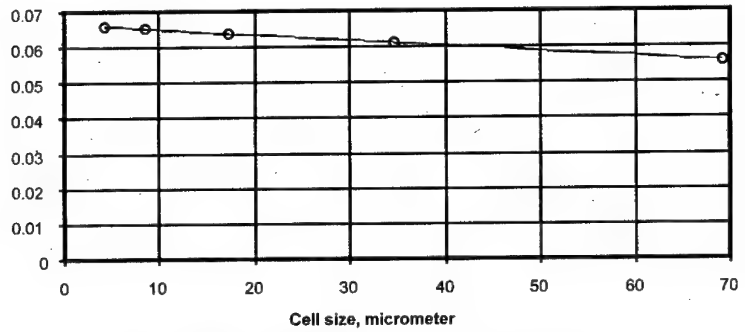

Figure 5 Variation of Relative Void Volume with Cell Size
Impact in AL 1145 at 185.6 m/s, 0.318 cm target

Our results show that to develop a mesh-independent damage computation we begin by providing a rate-dependent mechanical model with a suitable material viscosity and element size to stabilize the shape of the stress history. Then we make damage computations with the microfracture model and verify that the damage is not mesh dependent.

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MECHANISM OF MASS-TRANSFER UNDER THE SHOCK WAVE LOADING, INITIATED BY THE SHORT LASER PULSES

V.A.Putilin, A.V.Kamashev

Samara State Technical University, Samara, Russia

It is known, that motion of interknot atoms is more faster then motion of vacancies and its complexes. So, main contribution to mass-transfer metal contribute interknot atoms, form in process plastic deformation under passing of laser-induced shock wave .Process of generation the point defect and their displacement occur, basically, in front wave load. Efficient source interknot atoms be under laser-induced striking loading shallow defect, stair on screw and mixed dislocations. Moreover on initial stage deformation form stair, generate under its motion interknot atoms.

Under use for processing metal laser radiate with density power 10^9 W/crn^2 and duration pulse 30 ns be provided high rate entering energy, bring; brought about significant velocity heating and cool, reach order of 10^{10} K/sec, as well as to shaping shock wave high pressure (20 GPa) and significant warm-up gradient. The mechanism of interknot atoms transfer is defined by characteristics of laser-induced shock waves.

We have shown that if gradient pressure in front shock wave is more than $5*IO^{13}$ Pa/m, and a gradient of temperature in front of the thermal wave has the order of 10^7 K/m, then the passion of interknot atoms take place by shock and by thermal pulses. Under smaller value specified gradient concurated several mechanism carrying: thermoactuate driftage interknot atoms in front shock wave, their carrying moving by dislocations and also possible transfer as a result of grain-border slipping.

THE INFLUENCE OF MARTENSIT TRANSMISSIONS ON CONDITIONS OF SHOCK WAVE GENERATION IN CARBON STEEL UNDER THE INFLUENCE OF PULSE LASER RADIATION

A.V. Kamashev

Samara State Technical University, Samara, Russia

It is known, that generation of shock waves occurs under the influence of short pulse laser radiation on metallic target. Shock wave generation conditions will greatly changes if such target will be carbon steel. The reason is that in given material martensit polymorphic transition, capable to be a source of secondary shock waves occures simultaneously with spreading of shock waves. Investigation of primary and secondary shock waves interaction, as well as especiallity of tensed condition in such materials, is of great scientific and practical interest.

In this paper numerical modeling of generation of laser-induced shock wave in material, capable to martensit transformation, conditions is fulfiled.

For this purpose equation of knock-compressed solid state was analysed. The model of wave spreading with the use of wave equations system in private derives is created. Pulse of laser-induced shock wave of sol lion-type was prototyped by Heviside step-like function .

On base of numerical modeling it is shown that tensed condition in material, at martensit polymorphic conversion, distinguishs qualitatively and quantitatively from tensed condition in material with the same size springy modula, without martensit conversion. So for instance, under comparison of tensed condition in eutektoid composition of У8 carbon steel and in nickel, it was found, that in nickel the level of maximum compression tension under the same conditions, is nearly 2 times less. As a rezult it may be supposed that threshold of shock wave generation in martensit conversation is less than in material without analogical transmissions.

MATHEMATICAL SIMULATION OF DISK ROLLING BY METHOD OF LOCAL DEFORMATION TAKING INTO ACCOUNT COMPRESSIBILITY AND NON-STATIONARY CHARACTER OF FLOW

V.A.Bychenkov, A.V.Skovpen

Russian Federal nuclear Center-VNIITF, Chelyabinsk-70, Russia

Mathematical model describing material flow under conditions of structural superplasticity is developed, as well as explicit Lagrangian technique for computing process of disk rolling by method of local deformation. Method is proposed for solving three-dimensional spatial problem on the basis of two-dimensional approximation. Two working pairs of rollers are considered to be absolutely rigid bodies. Friction force between disk and tools is taken into account. A code is developed on PC which allows to calculated different rolling modes, determine forces imparted onto the tools, and stress and strain fields in a workpiece. A formula is determined for flow of titanium alloy BT9 at temperatures 900-950 ^{0}C describing experimental data on tension and slip of cylindrical specimens. Calculations are performed in different configuration of process of rolling disk made of alloy BT9, parameters of mathematical model are determined, and the model is compared to experiment in terms of force impact on the tools.

Apparently, for the first time in computational mechanics an attempt was made of solving numerically the problem of metal pressure processing with account of time evolution of slow process, compressibility and relaxation of material shear stresses. The code computes the process ~ 100 times faster than the software package ANSYS 5.3.

COMPUTER SIMULATION OF SHOCK WAVE PROCESSES IN TI-C SYSTEM IN THREE-DIMENTIONAL STATEMENT

V.A.Gorelski, V.V.Kim, V.B.Nikulichev, S.A.Zelepugin

Tomsk Branch of Institute for Structural Macrokinetics, Tomsk, Russia

A model for damaged multicomponent medium used in the computations is characterized by the possibility of microcavities (crack, pores) formation and evolution and the possibility of chemical reactions in condensed matter. The set of governing equations of unsteady adiabatic movements of compressible medium with regard for pores development and chemical reactions consists of the equation of the motion, continuity equation, equation of en-

ergy, kinetic equation of chemical reactions and equation of evolution of the specific volume of pores. Finite elements method is used for solution of the problem [1]. According to this method, a discrete model of the bodies are constructed which consists of a finite number of finite elements that are assembled by corresponding way. The equation of motion for a typical finite element is obtained using the principle of virtual velocities. The equations of motion for the set of finite elements are obtained by assuming that masses of the element nodes are equal to each other. The linear approximation for velocities within the element is assumed in the calculation.

A problem of non-symmetrical high velocity interaction of steel capsule with Ti-C stoichiometric powder mixture inside [2] with high-strength plate was numerically studied using a three-dimensional approach. The steel capsule has the outer diameter of 0.0762 m and length of 0.2286 m. The initial velocity of the capsule was 1000 m/s, the angle with plate was 15^0. The initial porosity of the powder mixture was 0, 0.2 and 0.6. Configurations, velocity fields, contours and dependencies of process parameters are presented. The peculiarities of the fracture of profiled cylinder capsule filled with porous reactants are analyzed. The influence of chemical reaction and initial porosity of the powder on the process is investigated.

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FLUCTUATIVE DECAY OF SHOCK WAVES IN THE NON-LOCAL THEORY OF DYNAMICALLY DEFORMED MEDIA

T.A.Khantuleva, Yu.I.Mescheryakov*

*Saint-Petersburg State University, *Institute of Mechanical Engineering Problems, Saint-Petersburg, Russia*

In a series of experimental investigations on the shock loading of some materials an anomalous high shock wave decay has been measured. Simultaneously, by using the interference technique for measuring the free surface velocity of shock loaded targets it has also been found an essential increase of the particle velocity dispersion. Microstructure investigations of recovered specimens has shown the presence of unusual regions of strain localization in cross-sections of specimens [1.2]. These regions have a shape of round cells and/or chains of cells,

which permits to believe them having the rotational (vortical) origin. Similar to the shear band the latters are elongated in the wave propagation direction crossing grain boundaries without deviation. Their nucleation is thought to be localized in the mixing layers on the boundaries of microflows moving with different velocities in the direction of wave propagation as a result of the structure and velocity heterogeneity of the shock compression of solids. In shock compressed solids the rotational cell diameter has been ascertained to be proportional to the difference in accelerations of adjacent microflows between which the rotation motion of a medium is initiated.

All heterogeneities arising during the dynamic straining may be related to the so-called mesoscopical scale level (0.1-10 μm) which occupies an intermediate position between atom-dislocation level and macrolevel.

At present there is no a satisfactory theory to describe the mesoscopical effects. Therefore, one needs in such approach which remaining to be macroscopical could take into account the processes of re-arrangements of inner structure of solid during the dynamic loading.

In the presented paper a new approach to describe structured media subjected to dynamic loading is developed [3-5]. The approach is based on similarity of behavior of dynamically loaded solid and nonstationary phenomena in hydrodynamics. However, it distinguishes in several essential aspects on the classic hydrodynamics. Firstly, it is a non-local method, i.e., it takes into account the state of medium not only in a local point of space but also long-range interaction of surroundings. Secondly, it self-consistently takes into account an influence of boundary conditions on the structure formation process, so that the scale of structure elements and kind of kinematical mechanism at the microlevel are the results of branching of total nonlinear task of dynamic straining. In particular case, when non-local parameter tends to zero, the weak-nonlocal approximation solutions coincide with the solution for the Newton liquid.

The main features of the proposed approach can be demonstrated in a principle problem for a plane elastic-plastic wave propagation in semi-space with relaxation processes. In case of uniaxial strain condition this task has the form:

$$\rho\,\partial \mathbf{u}/\partial t + \partial\sigma/\partial x = 0,$$
$$\partial\sigma/\partial t + \rho\,a^2\,\partial \mathbf{u}/\partial x = \partial\sigma^d/\partial t \qquad (1)$$

in our theory relaxation item of constitutive equation is written in a nonlocal form

$$\sigma^{d}(x,t) = \rho \mathbf{D}(x,t) - \mu_e \int \frac{dx'}{\varepsilon} \exp\left[-\frac{\pi}{\varepsilon^2}(x'-x-\gamma)^2\right] \partial \mathbf{u}(x',t)/\partial x' \quad (2)$$

Here **D** is the mesoparticle velocity dispersion, μ_e is the effective viscosity of medium, nonlocal parameter γ chacterizes a polarizing influence of boundary $x = 0$ on the state of medium and ε defines the radius of nonlocal correlations. A relationship between mass velocity decrease $\delta\mathbf{u}$ due to fluctuative motion of medium and dispersion gradient is obtained in the form:

$$\delta \mathbf{u}(x,t) = \int_0 (\partial \mathbf{D}/\partial x)\, dt$$

Thus, current value of fluctuative decay is equaled to gradient of mesoparticle dispersion while the total value of wave decay is determined by integrating over the rise-time of plastic front.

It was also shown that in case of **D** = const the wave propagation velocity decrease is also dependent on the mesoparticle velocity dispersion: $\mathbf{a}^2 = \mathbf{c}^2 - \mathbf{D}/c_f$, where c_f is an energetic capacity of fluctuations on the mesoscopical scale level and **c** is the sound velocity. In scope of a new theory such values as an effective viscosity of a medium, typical scales of internal structure formed by the nonlocal correlations were approximately defined in analytical form taking into account additional experimental data for mass velocity **u**, velocity dispersion **D**, and normal stress σ. The typical sizes of the internal structure in the normal direction to the wave were determined on a base of the well known shear flow problem and turned out to be coincided with those discovered in microstructure investigations in form of mesorotations.

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MODELING OF MESOFRAGMENT ROTATIONS IN MATERIAL UNDER DYNAMIC LOADING

P.V. Makarov, I.Y. Smolin, D.V. Shmick

Institute of Strength Physics and Materials Science, Siberian Branch of RAS, Tomsk, Russia

Earlier the authors found out local rotations of fragments of medium in front of shock wave and behind it in numerical modeling passage of plane shock wave instructural non-homogeneous media [1]. Results of further researches of rotations of separate fragments in the mesovolumes of polycrystalline material at passage of a shock wave are submitted in the present work.

A model taking into account appearance of unbalanced internal moments and non-symmetrical stress tensor at development of plastic shears in separate slip systems is suggested. Some results of modeling passage of plane shock wave in medium with unbalanced moment are submitted. Calculations based on this model have shown amplification of effect of plastic deformations localization. Dynamics of local rotations is investigated at passage of release wave.

For numerical researches the program based on the Lagrange approach with relax determining equations was applied.

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FEATURES OF NUMERICAL MODELING OF STRAIN LOCALIZATION AND FRACTURE AT THE NESOLEVEL IN METALS UNDER SHOCK WAVE LOADING

I.Y. Smolin, Y.P. Stefanov

Institute of Strength Physics and Materials Science, Siberian Branch of RAS, Tomsk, Russia

The paper is devoted to peculiarities of numerical description of strain localization, formation and opening of meso- and macro cracks at modeling of shock-wave deformation in mesovolumes of polycrystalline materials.

For simulation of strain localization processes on mesolevel it is suggested to take into account obviously the main structural heterogeneities of mesoscale: grains and their boundaries, various inclusions

and allocation of other phases. Thus, distinction of elastic characteristics and strength properties of different fragments of structure are taken into account in calculations. A through method of calculation is applied, when the area of localization was not set beforehand and only peculiarities of heterogeneity distribution result in non-homogeneous distribution of stresses and strains, and, consequently, appearance of shear bands.

For fracture modeling at shock wave deformation a method based on splitting of nodes of the Lagrange grid and formation of new free surfaces at opening of a crack is used. An integrated criterion of damages accumulation was used as a condition for generation and growth of cracks.

The finite difference scheme of the second order of accuracy in Lagrange variables with necessary changes in the determining equations of relax type and technique of splitting of grid nodes forms the basis for the used computer programs.

Examples of solving 2D problems in plane strain condition are considered. Results of modeling formation of zones of localized strain in various model mesovolumes of structural non-homogeneous medium at passage of plane shock wave and examples of modeling spall fracture are submitted.

NUMERICAL INVESTIGATION OF RELAXATION PROCESSES IN MESOVOLUME OF METALS IN SHOCK AND RELEASE WAVES

Romanova V.A., Balokhonov R.R. and Makarov P.V.

Institute of Strength Physics and Materials Science, Siberian Branch of RAS, Tomsk, Russia

An elastic-plastic medium response of relaxation type to dynamic loading has been numerically investigated. The subject under study was representative mesovolume, that is conglomerate of grains differently oriented to loading direction. The different orientation of grains is given by divergence of mechanical characteristics from average ones corresponding to macroscopic characteristics of the materials. In each grain the medium is considered as continuum and its behavior is defined by evolution of the dislocation continuum. Averaging the mechanical response to loading over the volume, we obtain macroscopic behavior consistent with experimental data. It is sense that mesovolume under study is representative - on the average it exhibits the mate-

rial macroscopic properties. An elastic-plastic model of relaxation type implies that deviatoric part of stresses depends on plastic strain rate. To construct the constitutive equation of relaxation type two approaches studied early were combined. At first, plastic strain rate in shock wave can be connected with evolution of dislocation continuum. The advantage of this approach is that the parameters of the model is of an obviously physical sense and can be found by means of independent experiments. But there are essential difficulties to simulate 2D problem because of a number of new parameters which would be defined. Therefore to calculate 2D representative mesovolume we used the conception about viscous nature of relaxation processes in shock waves. In this case, the shear stresses are sum of two functions, one of which depends only on accumulation plastic deformation and describes work hardening, and second one is connected to plastic strain rate and named as viscous stresses. In shock waves the viscous stresses are of an obviously physical sense and are difference between Hugoniout shock adiabat and Reliey line. The viscous stresses are in proportion to plastic strain rate, and coefficient of proportionality depends on plastic deformation and stresses. Function of relaxation coefficient was found out on the basis of experimental data on elastic precursor decay and 1D shock wave calculations using dislocation kinetics of plastic shears as mentioned above. It is shown that relaxation conception gives the adequate description of material behaviour at micro-, meso- and macroscale levels under high-rate loading, particularly under shock waves. Evolution of micro and mesostructures and also relaxation of macroscopic stresses in the region of non steady state shock fronts and release waves are investigated.

МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ВЗАИМОДЕЙСТВИЯ ИЗЛУЧЕНИЯ С ДЕФОРМИРУЕМОЙ ПРЕГРАДОЙ

Острик А.В., *Острик Е.А.

*ЦФТИ МО РФ, Сергиев Посад, *МФТИ, Москва*

В настоящее время имеется представительный набор математических моделей, описывающих взаимодействие излучения с конденсированным веществом для различных длин волн и плотностей потоков энергии. В зависимости от режимов воздействия, свойств материала преграды и окружающей среды эти модели существенно отличаются одна от другой. Но в том случае, когда нас интересует механическое действие излучения, возникающее благодаря гидродинамическому разлету паров вещества, та группа

процессов, которая определяет механические нагрузки на конденсированную преграду, оказывается практически одной и той же в широком диапазоне длин волн и описывается системой уравнений радиационной газовой динамики с учетом сдвиговых напряжений в твердом теле. Целью настоящей работы является построение достаточно общей математической модели, позволяющей исследовать механическое действие излучений оптического и рентгеновского диапазонов спектра. Такая модель необходима, например, при расчете воздействия на деформируемую преграду потока излучения, имеющего в своем составе кванты с сильно различающимися энергиями.

При расчете взаимодействия излучения с конденсированной средой применяются два альтернативных подхода: с представлением области сильно поглощающего слоя в виде движущейся поверхности разрыва и без его выделения. Введение дополнительного разрыва оправдано при рассмотрении действия излучения оптического диапазона, когда поглощающий слой тонкий и расположен непосредственно у границы твердого тела, т.е. является естественным разделением областей сопротивляющихся и несопротивляющихся сдвигу. В случае более жесткого излучения с энергией квантов E>1кэВ поглощающий слой не мал и его выделение, как правило, не делается, что снимает вопросы о кинетике фазового перехода и положении границы между сильно и слабо поглощающими областями. Плавный переход от твердого материала, сопротивляющегося сдвигу, к газообразным продуктам испарения осуществляется заданием предела текучести в виде функции от температуры или внутренней энергии, обращающейся в ноль при превышении некоторых заданных значений этими переменными. В предлагаемой модели одновременно реализуются оба рассмотренных случая тонкого и толстого поглощающих слоев. Для этого, помимо введения разрыва, производится деление воздействующего потока излучения на две части: мягкую, ответственную за движение разрыва и не проходящую через него, и жесткую, поглощаемую только объемно. При этом тепловое излучение плазмы относится к мягкой части потока и полностью поглощается на разрыве.

Математическая формулировка задачи содержит: систему локальных законов сохранения, записанных для одномерного случая в лагранжевых координатах; широкодиапазонные уравнения состояния и зависимости спектральных массовых коэффициентов поглощения от температуры и плотности; уравнения для расчета

сдвиговых напряжений (используются соотношения дислокационной модели, корректно описывающие затухание волн напряжений в металлах); уравнения переноса излучения; соотношения на разрыве и дополнительные условия на нем, следующие из рассмотрения кинетики в поглощающем слое (используются модели кнудсеновского слоя испарения Анисимова-Романова-Найта и изотермического скачка). Перенос теплового излучения плазмы описывается приближенно на основе синтеза двух моделей для предельных случаев (объемного высвета из внешних оптически тонких слоев и лучистой теплопроводности для внутренних оптически толстых слоев). Расчет распространения и поглощения жесткой части излучения осуществляется методом Монте-Карло с учетом фотопоглощения, когерентного и комптоновского рассеяний, а также флюоресценции.

Сформулированная система дифференциальных уравнений с краевыми условиями решается конечно-разностным методом, представляющим собой полностью консервативную схемы второго порядка точности с неявной аппроксимацией искусственной вязкости. Получающаяся система алгебраических уравнений линеаризуется по Ньютону и решается методом матричной прогонки с последующими итерациями.

Результаты расчетов приводятся в области изменения энергий квантов E=0,1...10кэВ, где, во-первых, проходят границы применимости моделей с тонким и толстым слоями поглощения, а во вторых, имеет место максимальная механическая эффективность воздействия.

SCALING PHENOMENA IN DEFECT ENSEMBLES AND STRUCTURE OF STRESS WAVES IN SHOCKED MATERIALS

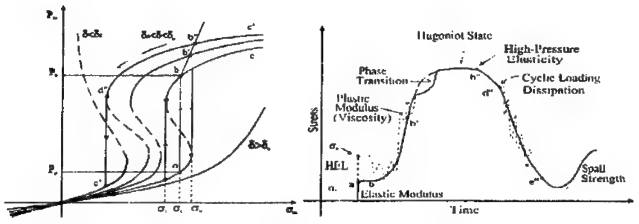
O.Naimark, J.-L.Lataillade*

*Institute of Continuous Media Mechanics, Perm, Russia *LAMEF-ENSAM, Talence, France*

The experimental study of solid behavior under strong shock wave loading reveals pronounced features of the self-similarity that is typical for essential nonlinear systems in the condition of the non-equilibrium transitions. The understanding of these regularities is important both from point of view of fundamental aspects of plasticity and failure and

for the explanation of specific relaxation ability in shocked materials. The self-similar solid response on shock wave loading was investigated first by Sakharov's group [1] when the surprising fact of practically constant value of viscosity $\eta \approx 10^4$ *Pz* was established for all investigated matter (aluminum, lead, water and mercury) for the strain rate range $\varepsilon \sim 10^4 - 10^7\ s^{-1}$. The universal dependence of strain rate as the fourth power of the shock stress was observed also by Swegle and Grady [2] at the same range of the strain rate.

Fig I : Defect density evolution (a) and profile of shock wave (b).



The self-similarity features of solid response on impact were studied by Naimark's group [3] for the explanation of the overloading effect (the so-called, "dynamic branch") under spalling. Having the goal to study the influence of the mesodefects on relaxation properties and failure in shocked materials the statistical thermodynamics of typical mesoscopic defects (microcracks, microshears) was developed by Naimark [4,5,6] using the experimental data established the linkage in the evolution of ensemble of these defects with relaxation properties of solid and transition to fracture. Specific microscopic (and macroscopic) tensor parameters playing the role of order parameter and describing the mesodefects as localization of corresponding symmetry group of the translations (from point of view of the gauge field theory) were introduced. Statistical description based on the solution of the Fokker-Plank equation allowed the establishment of the free energy form of solid with these types of defects and continuum evolution equations describing the influence of defect kinetics on relaxation properties and transition from disperse accumulation of defects (damage) to fracture.

The essential result of the developed approach is the opportunity to describe qualitative different material responses (plasticity, transition to fracture) without the usage of yield (quasi-static) characteristics of phenomenological plasticity and fracture theories but as inherent nonlinear properties of defect ensemble. The correspondence of nonlinear material responses in terms of "defect density tensor p_{xx} - stress σ_{xx} " and shock wave profile (established by Naimark) are presented in Fig la and b.

The qualitative different solid responses are determined by the value of the dimensionless parameter δ characterizing by two natural scales in heterogeneous materials:

- the mean size of the defect nuclei (related to the size of structural heterogeneity for instance the grain size)
- the correlation radius of the stress fluctuation caused by the defect growth.

The decrease of δ reflects qualitative changes of solid response on the defect growth that are observed for submicrocrystalline state ($\delta > \delta_*$), for ductile ($\delta_* < \delta < \delta_c$) and quasi-brittle ($\delta < \delta_c$) responses, where δ_c and δ_* are the bifurcation points determined by the statistical theory. The free energy form reflecting the diversity of above responses could be represented as the fourth power Ginsburg-Landau expansion in term of the p_{xx} order parameter (for the uniaxial loading):

$$F = 1/2\, A_0 (1 - \delta/\delta_*) P^2_{xx} - 1/3\, B\, P^3_{xx} - 1/4\, C_0 (1-\delta/\delta_c) P^4_{xx} - D\, \sigma_{xx} P_{xx}$$

where A_0, B, C_0 and D are material parameters. The sharp change of the material sensitivity on the defect growth due to the loading (for instance, the qualitative transition from plastic relaxation to the failure kinetics) is described as the dependence of δ on P_{xx}, $\delta = \delta_0(1 - \beta P_{xx})$. The developed approach allowed us to propose the interpretation of characteristic parts of the shock wave profile. The explanation of the time dependent H.E.L. is given as the consequence of the strain rate dependent depth of the penetration of the nonlinear system into metastability area (σ_I - σ_{II}, point *a*). The shock-induced softening is realized due to the sharp increasing of the defect density tensor (in fact, deformation caused by defects) during the orientation ordering in defect ensemble. It is accompanied by the generation of the spatial-localized structures of the plastic instability in the form of solitary waves (Post-Yield Flow Instability, *a* - *b* transition). The viscous flow at the steady shock front is realized due the change of the sensitivity of materials to the defect growth. It leads to the decrease of the current value of the δ parameter and as the consequence to the "extension" of the non-

equilibrium transition ($b \rightarrow b' \rightarrow b''$) due to the change of the free energy form (playing the role of plastic potential) under the stress increasing.

Taking in view the driving force of this transition - $\partial F/\partial P_{xx}$, the kinetics for P_{xx} reads

$$P_{xx} = - Lp\, \partial F/\partial P_{xx} \mid_{\sigma b \rightarrow b'} \propto L_p C_o \beta G^{-4} \sigma^4_{xx}$$

where Lp is the defect kinetic coefficient, G is the shear elastic modulus of the material.

The stable fourth power dependence of strain rate on stress could be observed (Fig la) for a→ b→ b'→ b"... on transitions when the maximum depth of the penetration in the metastability area is reached. It is provided by the approaching $\sigma_I \rightarrow \sigma_{II}$ (Fig lb) for the critical strain (or stress) rate ($\varepsilon \sim 10^4 - 10^7 s^{-1}$).

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SESSION " Detonation Physics of Energetic Materials"

Co-Chairmen:

A.Borisov - Institute of Chemical Physics, Moscow, Russia

J.Forbes - US Lawrence Livermore National Laboratory, Livermore, USA

DETONATION PHYSICS AND CHEMISTRY: EXPERIMENTAL STATE OF THE ART

Stephen A. Sheffield, Co-Workers: Ray Engelke, Rick Gustavsen, and Lloyd Davis

Los Alamos National Laboratory, Los Alamos, NM 87545

Detonation and initiation studies in the past have led to a large body of knowledge concerning the nature of these phenomena. While much has been learned, there are some areas where very little is known, e.g., the chemistry in the detonation reaction zone – almost nothing is known about the chemical species and reactions that occur in this regime. However, with ultra-fast laser based measurements now available in many experimental areas, more studies are being done that are leading to increased understanding of the reaction processes.

This presentation will not be a comprehensive review of work that has been done in the past, but will concentrate on work familiar to and of interest to the author. An extended relationship with Ray Engelke and more recent associations with Rick Gustavsen and Lloyd Davis have helped a great deal in my understanding in this area so I have listed these as co-workers in this presentation.

Nitromethane (NM) is one of the more simple liquid explosive materials. It has been studied in some detail over the last 40 years but the first reaction steps are still being debated. There are now hints of what the reactions are, based on the work of Engelke et al.[1] at Los Alamos and that of Gupta et al.[2] at Washington State University (WSU). There seems to be two different areas of thinking, relative to the initial chemistry occurring in NM; those who think homolytic reactions are important (namely, C-N bond scission) and those that believe that normal condensed phase high pressure reactions (condensation reactions) dominate. The first group is composed mainly of workers that believe gas-phase chemistry is applicable, while the latter group is composed mainly of those associated with condensed-phase high-pressure chemistry studies. In order to better understand dynamic shock chemistry of organic liquids, a discussion of some aspects of this area is given.

In the past many organic liquids have been studied under shock conditions. A few of them have addressed shock-induced reaction, e.g., studies in Russia by Yakushev et al.[3,4] and by Richard Dick[5] at Los Alamos. A number of the liquids were found to have cusps in the experimental Hugoniots that were attributed to shock-induced chemistry. Work done at WSU on carbon disulfide[6] led to a method of uncovering evidence of shock-induced reactions in liquids. The universal liquid Hugoniot developed by Woolfolk et al.[7] is an empirical form that was developed by fitting to the Hugoniot data of a number of liquids available at the time. This relationship is:

$U_s = 1.37\ C_0 - 0.37 C_0 \exp(-2u_p/C_0) + 1.62\ u_p$

where U_s is the shock velocity, u_p is the particle velocity, C_0 is the sound speed at ambient conditions. If the sound speed is known, a U_s-u_p Hugoniot can be calculated. From this other Hugoniot parameters (e.g. pressure) can be calculated if the initial density is known.

Hugoniot data for a large number of liquids have been plotted and matched with the universal liquid Hugoniot; it provides a very good estimate for the experimental Hugoniot. Non-reacting liquids including mercury, water, n-hexane, and liquid argon, were looked at as well as reacting materials including carbon disulfide, benzene, and toluene. The latter show large deviations of the data from the empirical Hugoniot above the cusp.

Many organic materials show reactions in which the products are more dense than the reactants, e.g. benzene. Explosive materials have products that are less dense than the reactants, e.g. nitromethane. These two conditions represent the two ends of a spectrum. There are undoubtedly materials that react to give products without an accompanying large volume change. Carbon tetrachloride may fall in this category.

Dremin et al.[8] published a figure depicting the wave profiles expected from shock-induced reactions in materials where the products were more dense than the reactants. These range from a two-wave structure when the first wave is not overdriven, to a steady wave with a "notch" where the reaction is occurring. Two-wave structures have been measured in single-shock experiments in acrylonitrile[4] and phenylacetylene.[9]

In order to determine the reaction associated with these Hugoniot cusps in organic materials, Engelke and Blais[10] studied single-crystal anthracene in a mass spectrometer system. Anthracene crystals were shocked by explodingfoil-driven Kapton flyers. Anthracene was found to be dimerizing when shocked to pressures above the cusp. This is evidence of a condensation reaction, exactly what is expected based on high pressure chemistry.

What does this have to do with chemistry in initiation and detonation? Blais et al.[1] have done similar mass spectrometer measurements on detonating NM. They found that new chemical species are observed in the reaction zone which are the result of condensation reactions where two or more NM molecules combine to form molecules more massive than NM or produce molecules in which numerous nitrogen atoms are present. This is evidence that condensation reactions occur in NM under detonation conditions.

The 1-D ZND model of a detonation appears to be a reasonable approximation for what is going on in a number of explosive materials. Dremin has proposed that a 2-D phenomena, similar to what occurs in gas phase detonations, also occurs in condensed phase detonations on some scale – this has yet to be carefully verified. We have measured the reaction zone of detonating NM interacting with a Plexiglas window using a VISAR interferometer system. The profile from this measurement is shown in Fig. 1; it agrees well with the ZND model when the appropriate impedance matching is done. Similar measurements on PBX9501 show the same thing. Similar reaction zone studies are also being done by Tarver et al.[11] at LLNL in the USA and by Fedorov et al.[12] and Lubyatinsky et al.[13] in Russia.

Recently we have measured sound speeds on a number of liquid explosives and estimated detonation parameters for them. These include bromonitromethane (BrNM), isopropyl nitrate, and hydrogen peroxide. We have made several measurements on BrNM, comparing it to NM; some interesting information has resulted. BrNM appears to have a von Neumann spike pressure about double that of NM. Much of this is probably a density effect. Its sensitivity to shock input is about the same as NM.

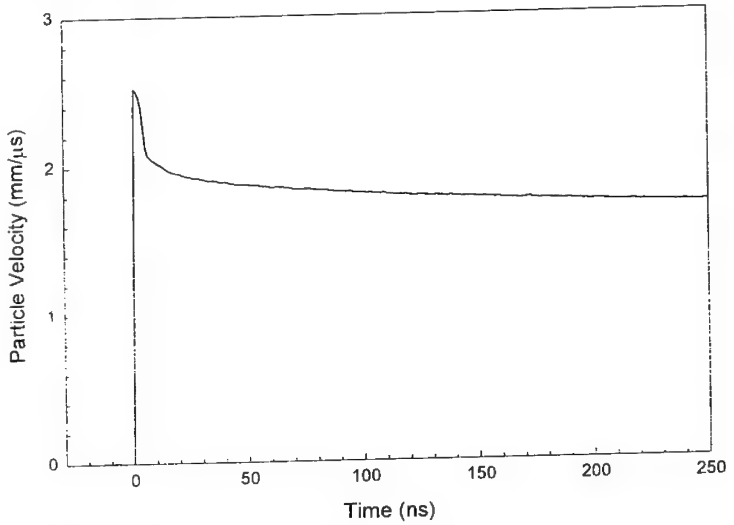

FIGURE 1. Interface particle velocity profile of a NM detonation wave interacting with a Plexiglas window.

We have done shock initiation measurements on PBX9501 in which as many as 12 in-material magnetic gauges have measured the shock-to-detonation transition with very nice particle velocity profiles. In addition, a "shock tracker" provided an distance-time plot for the shock front, showing clearly the turn over to detonation. These experiments will be discussed in de-

tail by Rick Gustavsen later in this conference. Similar studies are also being done with manganin gauges by Urtiew, Tarver, Simpson, et al. at LLNL.[14]

In summary, a number of experimental studies have recently been done or are being done that add interesting new information to the physics and chemistry of detonation and initiation. If these studies can continue, important new understanding will result, both with respect to the reaction chemistry and the detonation reaction zone. In addition, studies on new explosive materials are also adding interesting new information.

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DETONATION FRONT IN HOMOGENEOUS AND HETEROGENEOUS HE

A.V. Fedorov, E.V. Zotov, G.B. Krasovski, A.V. Menshikh, N.B. Yagodin

Russian Federal Nuclear Center-VNIIEF, Arzamas-16, Russia

There is presently no completed physical model of detonation. The problem to determine basic parameters of detonation wave for particular HE formulations is still urgent. This paper gives description of experimental and numerical-theoretical researches of the detonation front structure to construct equation of state of nonreacted HE in wide range of pressures, to determine value of Neumann spike and width of the chemical reaction zone for group of mixture HE.

Formulations, based on HMX, RDX, PETN, TNT, were studied as heterogeneous HE. Liquid HE basing on tetranitromethane and fluorine nitroform, were used as homogeneous HE. Particle velocities vs. time with nanosecond time resolution were recorded by laser interferometric Fabry-Perot and ORVIS methods at the HE window interface border.LiF,CaF2 crystals, water and other substances were used as window materials.

Neumann spike values were determined, which 1,4-1,8 times exceed the Jouget state in value for different HE. For studied HE the Jouget state parameters and chemical reaction zone width were determined as well. Numerical simulations of the detonation front structure was performed. Good agreements between numerical and experimental data was obtained.

SHOCK WAVE INITIATION OF LIQUID EXPLOSIVES

M.F.Gogulya, A.Yu.Dolgoborodov, M.A.Brazhnikov, S.A.Dushenok*

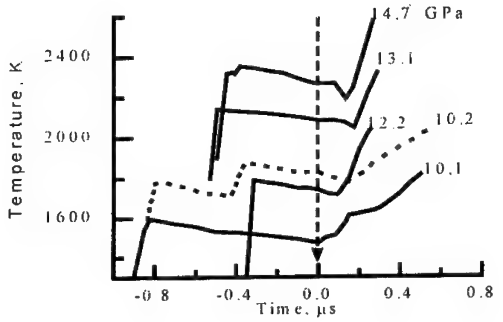
*Institute of Chemical Physics, Moscow, * "Technology" Research Center, Saint-Petersburg*

Shock wave initiation of liquid explosives (LE) was experimentally investigated: bis(2-fluoro-2,2-dinitroethyl)formal or (FEFO), isopropylnitrate (IPN) and 1,6-diazido-2-acetoxyhexane (DA). According to the classic model, a shock wave initiation of chemical reaction in the homogeneous HE occurs through volumetric heating of substance under compression, and the macrokinetics of decomposition obeys Arrenius law, thus the experimentally determined parameter is the time of delay of adiabatic explosion. The experiments on determination of this parameter with the help of an optical pyrometer were carried out in the following way: the initiating shock wave (ISW) enters LE from liquid indicator (in the present work these are bromoform or tetrachlormethane) with the known Hugoniots and dependences of radiation intensity on pressure. To prevent LE and indicator mixing, the polypropylene film of 20 microns thickness was located between them. It was expected that first the radiation of SW front in the indicator would be registered, then radiation of the indicator in a wave reflected from LE and, finally, LE own radiation would be registered. It was supposed that LE would remain transparent up to the moment of sharp intensification of chemical reaction. The results with IPN and DA have shown the close tendencies in behavior of these explosives under ISW. They are something different from the classic model. The profiles of brightness temperature allow allocating area of a supervelocity detonation, which temperature for IPN and DA can be estimated as 1800 K (with ISW pressure 8.0 GPa) and 2050 K (with 13,1 GPa) respectively. At the same time, further we observed the rather delayed site of overdriven detonation formation. For IPN it was determined, that even insignificant decrease of ISW pressure may result in spreading of supervelocity detonation zone. Increase of ISW pressure up to 9,8 GPa results in disappearance of area of gradual radiation increase (including area of supervelocity detonation), instead of it there is an increase of radiation up the moment of formation of a quasi-steady detonation. The change of radiation character for this LE allows receiving only approximate time delays in adiabatic explosion. For IPN at a pressure of 8,0 GPa the measured time delay is measured to be 0,1 ÷ 0,15 μs, at 9,8

GPa the initiation was practically without delay. For DA at 13,1 GPa the delay is about 0,25 μs. Initiation of chemical reaction in FEFO does not correspond to the model of thermal explosion even approximately. The brightness temperature profiles of radiation emitted from indicators and FEFO at various intensities of ISW are shown in figure enclosed. After ISW entering into FEFO (in figure it is marked by an arrow) at first the plateau is observed. Its duration decreases with growth of ISW pressure. Then the decrease of radiation and further rise is registered. The estimations show that temperature of shock compression FEFO with ISW pressure 14,7 GPa does not exceed 1200 K. Extrapolation of temperature time history at the minimal ISW pressure on the moment of an SW entering in a liquid does not give values less 1400 K. It can indicate that own radiation immediately appears in FEFO. At pressure higher than 10.1 GPa the experimental records do not give the qualitative changes of radiation intensity that could be expected due to the difference of compressibility of indicator and FEFO. The rate of radiation increase with changing of pressure in the range of 12 - 15 GPa practically does not vary, and at the same time it is mach more than the rate of growth fixed at pressure 10.1 GPa. Possibly, changes in the mechanism of initiation occur in the range of 10 - 12 GPa, i.e. in macrokinetics of observable processes.

Thus, the experiments have shown, that the macrokinetics of process a shock wave initiation in real LE differs from the simplified classical model. Specific features of chemical reactions development, caused by differences in molecular structure of explosives, require a new theoretical model for the description of decomposition a homogeneous HE with a shock wave compression.

The work was supported by Russian Foundation for Basic Research (Grant №97-03-32000a).



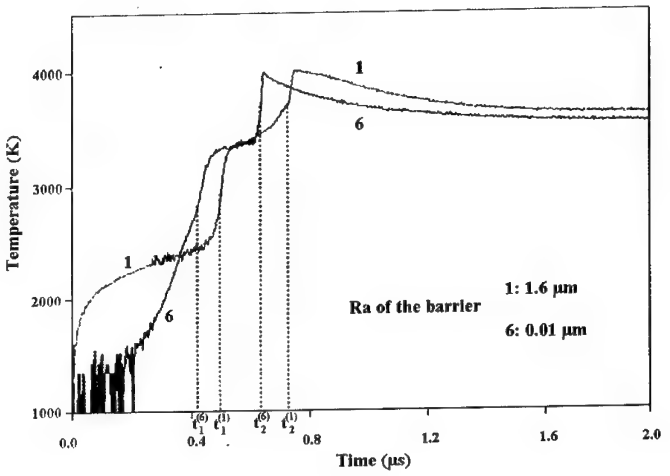
APPLICATION OF A FAST OPTICAL PYROMETER TO STUDY THE SHOCK-TO-DETONATION TRANSITION IN NITROMETHANE

B. Leal, H.N. Presles*, G.Baudin, B.A.Khasainov[O]

*DGA/Centre d'Etudes de Gramat, Gramat, *ENSMA/Laboratoire de Combustion et de Détonique, Futuroscope, France, [O]Institute of Chemical Physics, Moscow, Russia*

The mechanism by which detonation of a homogeneous high explosive (HE), especially nitromethane (NM), is initiated has for 40 years been the subject of numerous experimental and theoretical studies, i.e. [1,2]. The classical homogeneous model [1] assumes an adiabatic thermal explosion at HE/driver interface which results in formation of a superdetonation wave propagating in a compressed medium. If the thickness of the explosive is sufficient, the superdetonation overtakes the leading shock wave and then decays to the steady quasi-CJ detonation wave. Campbell *et al* [2] and numerous subsequent studies produced considerable support for this homogeneous model. However, a number of obscure points persist concerning superdetonation build-up (how, where and when does it occur?).

For these reasons we started an experimental study of the shock-to-detonation transition (SDT) in NM using a pyrometer operating in 6 wave lengths (500, 650, 850, 1100, 1270 and 1510 nm) and covering a wide range of temperature (1500-6000 K) with a 3-ns rise time. Complementary data, required to interpret the temperature signals and get a better understanding of the phenomena governing the initiation of NM, are obtained from three other non-intrusive techniques such as (i) Fabry-Perot interferometer for recording the transfer plate velocity history during initiation, (ii) polarization monitoring and (iii) piezoelectric pins located at measured depths in the explosive. The pins and capacitor placements were chosen in order not to disturb the region of one-dimensional strain monitored by the pyrometer and the Fabry-Perot interferometer. The NM (with a 1.134 g/cm^3 density and spectroscopic purity >99%) was initiated using an 11-m long, 98-mm diameter smooth bore single stage powder gun capable of accelerating projectile to velocities up to 2400 m/s. In order to guarantee a simultaneous shock build-up process at the NM interface, experimental set-up is adjusted so that tilts are better than 2 mrad.



Here we focus mainly on the dependence of the SDT on the roughness of the barrier plate/NM interface. The figure displays two records of the luminance temperature (λ=850 nm) of NM subjected to a shock pressure of 10 GPa at two values of the roughness (*Ra*) of the barrier (0.01 and 1.6 μm). The time t_1 is identified with the induction delay (the superscript 1 or 6 refers to the experiment number) and at time t_2 the superdetonation overtakes the leading shock front. These signals are consistent with the classical homogeneous initiation model [1] except for the first part during which their should be no radiation. On the contrary and particularly in the case of larger *Ra*, a radiation is emitted very quickly just after the passage of the shock front. This radiation could be due to local hot spots [2]. In the considered range of interface roughness these events do not seem to affect greatly the following transition to detonation, however that could be not the case with larger roughness [2]. So, pyrometer records of very early radiations during SDT demonstrate local heterogeneous behaviour of NM in SDT process.

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STRUCTURE OF THE DETONATION WAVE IN TNT

V.K. Ashayev, G.S. Doronin

Institute of Machine-Building, Dzerzhinsk, Russia

The curves of shock wave damping in plexiglass targets loaded with TNT charges of different length are investigated by the technique of laser measurement of wave velocities (LMWV) [1]. The structure of the detonation wave and the parameters of steady detonation are determined for pressed charges with the density of 1.58 g/cm^3.

The intersection possibility of the shock Hugoniot of the initial explosive in P-V coordinates and the detonation Hugoniot of the explosion products is shown analytically. The structure of the overshoot wave in TNT above the intersection point of the shock Hugoniot of the explosive and the explosive products is investigated by the LMWV method. The overshooting was provided by loading with aluminum firing pin having the flight velocity of 4.7 km/s.

It is stated that in this case on the P-U curve the parameters of the shock-wave front in TNT correspond to the parameters in the intersection point of aluminum retardation curve with shock Hugoniot of the explosion products, but not with the shock Hugoniot of TNT. It is verified by direct measurements of the overshoot velocity.

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MATTER DETONATION UNDER EXTERNAL INTERFERENCE - GENERALIZED CONCEPT OF SHOCK AND DETONATION PHYSICS

V.I.Tarzhanov

Russian Federal Nuclear Center - VNIITF, Chelyabinsk-70, Russia

The Hugoniot of the explosive gas detonation products by the additional energy introduction into the detonation front or its withdrowal from the front is written and analyzed:

$$P(\xi\eta - 1) - \xi - Q + \eta = \pm\sqrt{\frac{\Omega(1-\eta)}{P-1}},$$

where $= \frac{V}{V_0}$, $= \frac{k+1}{k\ \ 1}, Q = \frac{2q}{p_0 V_0}, \Omega = \frac{2S}{p_0^{3/2} V_0^{1/2}}, P = \frac{p}{p_0}$ –

dimensionless parameters;

V_0 and V – initial and final specific volumes of gas; p, p_0 and ε, ε_0 – pressure and internal energy behind and before the front; q – specific chemical energy release; S – power density of external energy adding into front (withdrowal from the front).

It is shown that this equation describes all self–supporting and sustained from outside stationary detonations and shock compression regimes:

– chemical detonation in Jouget, super–and undercompression regimes by $Q = 0.....\infty$;

– superheated detonation in Jouget, super–and undercompression regimes by $\Omega = 0....\infty$;

– cooled detonation in Jouget, super–and undercompression regimes;

– light detonation in inert matter in the same three regimes;

– shock wave compression of a chemically inert matter.

The curve of the Jouget states for matter in the enumerated processes is found:

$$\eta = \frac{P(\xi + 1)}{(2P - 1)\xi + 1}.$$

The boundaries of the cooled detonation existence arear are determined.

ON TNT COMBUSTION UNDER SHOCK COMPRESSION CONDITIONS

V. M. Bel'skii, R. A. Ibragimov

Russian Federal Nuclear Center-VNIIEF, Arzamas-16, Russia

When developing kinetic models of high-explosives (HE) decomposition behind the front of shock waves, it is commonly supposed that excitation of chemical reaction of explosive transition occurs following nucleation mechanism, and its extension over the whole HE volume takes place in the form of layer-by-layer combustion. That is why dependence of linear combustion velocity on pressure having the simplest form $U=BP^n$ is obviously included in the mathematical formulation of

the kinetic law. It is evident that for successful mathematical modeling of the detonation regime formation process it is necessary to know their numerical values with sufficient accuracy and precisely under conditions of shock compression.

This paper presents some results obtained by study of TNT combustion regularities under shock compression conditions. It is demonstrated that TNT has, at least, 2 areas with different values of constants, namely, $2,6 \le P \le 12,5$ and $P \ge 12,5$ GPa in the pressure range $2,6 \le P \le 20$ GPa. The values are not changed inside of each area. Information, needed for analysis, is obtained by experiments on initiation of pressed TNT by pulse with short duration. Analysis of experimental results is performed with use of the theory of nonstationary combustion.

MECHANISMES OF INITIATION CONFINED EXPLOSIVE CHARGES SUBJECTED TO FRAGMENT IMPACT

A.Pyryev, V.S.Soloviev

Moscow State Technical University, Moscow, Russia

Fragment impact is exposed to shock-wave, temperature and mechanical stimuli on confined explosive charges. These initiating factors depends on loading conditions, charge arrangement, explosive and fragment characteristics. He explains variety of answerback reactions charge, basic of which are: inert behaviour, stationary burning, transitive nonstationary modes (explosion) and detonation.

Shock-wave initiation of detonation is the most investigated. Explosion and burning realized only at perforation of case. Fragment velocity is lower than that shock-wave initiation threshold. Fragment impact studies are based on a deflagration to detonation transition phenomenon. Therefore it is important to investigate perforation case of explosive and ignition mechanisms of explosive by penetrating fragment.

The x-t diagram of perforation and penetration process of an plug is constructed on the basis of theoretical estimations. Different perforation mechanisms of case by thickness of 4-15 mm were marked in the tests with steel spherical fragments of weight 4-15 g and the velocity 500-1900 m s^{-1}. In particular, fragment punches a fuse and original ring element will be formed. Destruction of a fragment at perforation is played the large role in perforation and ignition mechanisms of explosive.

By results of tests in coordinates "the fragment velocity - thickness of a steel case" is constructed the diagram for determination of answer-back reactions (no perforation, perforation and no reaction, hydro-shock, local explosion, explosion, detonation) of composition TG40/60 to impact of steel fragment of weight 8 g. The boundary for the explosion/no response regime is the ballistic limit of the case material thickness of 6-15 mm. Decreasing of the case material thickness from 5 to 4 mm lead to transition from explosion to local explosion.

Probable transmitting (ignition from fragment) and dissipative (macroscopic shear deformation, shear band in explosive et al.) mechanisms of ignition explosive due to the penetration process driven and motionless of a fragment are resulted and classified.

DECOMPOSITION OF SHIELDED HE CHARGES AT NEAR TRANSONIC REGIME OF ELONGATED IMPACTOR

S.G.Andreev, G.A.Prudensky

Moscow State Technical University, Moscow

Test data on jet action of micro shaped charge (SC) on high explosive (HE) charges, which either were placed in strong closed shells, or had free cylindrical surface, but were necessarily shielded on the side of SC action, are presented. In a number of experiments HE were shielded also on the side of jet outcome from a charge. Micro SC of mass of 0.8 g had copper liner with mass of 0.3 g and base diameter of 12 mm and were located at a distance of 30 mm from the front (facial) steel shields of thickness from 2 to 10 jet diameter. Charges of mass from 5 to 50 g were made from pressed sensitized RDX, sensitized RDX, sensitized RDX with 20 % additive of aluminum powder, pressed TNT, molten TNT (with a various structure) were studied. The values of the product of jet velocity square by its diameter didn't reach a criterion value, needed to initiate the detonation in studied HE directly, and low-order explosive processes localized to a various extent were initiated in a HE charge. The velocity of jet penetration was less than sound velocity in HE. This feature in addition to the influence of a facial shield results in a pressure impulse form, differed from the conventional shock-wave (SW) impulse in a considerable time of pressure rise up to maximum at HE particles, at which a chemical reaction took place then.

When analyzing the results, analytical estimations of pressure distribution and deformation rates in jet region (supplemented by the results of numerical modeling with the help of the V. Kolpakov's computation complex "KOLDUN") and the data obtained by experimental method of post-effects in thin test layers (TL) are used. In this method HE TL from 1 to 5 mm thick are placed in a block of shields and plates of "inert physical-mechanical substitute of EM" made of fluoroplast and pressed salt with paraffin. TL were placed both in contact with shields, and at different distances from them. Post-effects were fixed at hardening of compound, melted in jet cavity, and were analyzed with the help of various sections of samples.

From the analysis a number of features were revealed in particular. At a lack of influence of a HE layer, adjoined to the upper shield, a shaped charge jet (SCJ) doesn't produce any considerably (more then tenth of cavity diameter) self-propagating reaction. The reason of that is the presence of a cavity in the region of short pressure impulse with a fuzzy shock front in the region of SCJ head. A considerable HE decomposition in the cavity region is observed only under the influence of reaction products flow from the upper shield to the cavity bottom. As the result of this flow the volume of decomposition zone in HE charges with open free surface reached values from 20 to 50 cavity volumes in chemically passive medium.

Products of the charge reaction from this volume look and smell like products of "low-temperature" ($T<500$ K) thermal decomposition and possess low expressed blasting action.

The HE reaction in layers, adjoined to the facial shield, depends on original charge microstructure like the decomposition of HE with nonhomogeneous structure in weak shock waves. It is explained by the fact, that fuzziness of the fore shock front of pressure impulse in this charge layers was insufficient for the considerable appearance of the effect of shock wave HE desensitizing.

In HE layers outlying from the facial shield the mechanism of influence of original charge structure is apparently different. There the fuzziness of the fore front of pressure impulse is essentially bigger, than near the shield, and results in the shock-wave HE desensitizing (the decrease of decomposition spot concentration). Therefore the original charge structure influences already the late stage of decomposition on account of its definition of charge damage degree in divergent flow behind the wave front near the cavity. The damage of charge structure makes easy the development of convection mechanism of HE decomposition around the cavity. In addition damaged structure appears to

be more sensible to an action of tail parts of imperfectly straight SCJ, which can interact with cavity sides.

The reflection of SCJ and a jet of reaction products flowing along the cavity from the back shield increases considerably the volume of decomposed HE and enhances blasting and explosive action of HE charge. Mainly this enhancement is also connected with the development of charge structure damage and convection mechanism of HE decomposition.

Experiments provide the base to suppose, that near the facial shield in the region of a cavity surface under deformation conditions at pressure of - 10 GPa and velocity of ~10^6 1/s during ~1μs chemical reaction of fluoroplast, resulting in products formation of black color, takes place.

LAUNCHING OF PLATES BY PRODUCTS OF OVERCOMPRESSED DETONATION OF EXPLOSIVE CHARGE WITH DECREASING DENSITY

V.M.Belskii, E.E.Lin, E.N.Pashchenko, B.P.Tikhomirov, I.P.Khabarov

Russian Federal Nuclear Center-VNIIEF, Arzamas-16, Russia

With use of the method of comparison of steel plates flight energies, accelerated by explosion products of charges with variable and uniform (maximum) densities under similar conditions, possibility is investigated to increase the coefficient of energy take-off from HE charge by contouring its density.

Charge of explosive and the launched plate in one type of experiments were enclosed in massive cylindrical casing with wall thickness of 25 mm, in the other type of experiments they had no casing. The x-t-diagram of plate motion, accelerated by explosion products, was directly determined in experiment with help of 8 electrical contacts of the pin type. Time intervals were measured with error of ± 20 ns.

The law of density decrease in charge was specified as [1,2]

$$\rho = \rho_0 \left(1 - \frac{x}{L}\right)^{\delta}$$

where δ=0; 0.2; 1, ρ_0 - initial density in section x=0, L - tentative length, where ρ turns into zero.

The energy take-off coefficient increase for charges with δ=0.2, placed in heavy steel shell, is tabulated in the table.

Value of the energy take-off coefficient (η) of steel plate from HE charge, placed in casing.

D	m	$h/h_{d=0}$
0	0.4	1
0.2	0.4	1.15
1	0.4	1
0	0.3	1
0.2	0.3	1.10
1	0.3	1
0	0.2	1
0.2	0.2	1.05
1	0.2	1

It is testified that curves of calculations for integrals of kinetic energy of overcompressed detonation products flow correspond to experimental values of kinetic energy of plates.

FOCUSING CONDITIONS AT THROWING METAL SHELLS OF VARIABLE THICKNESS BY DETONATION PRODUCTS OF CONDENSED EXPLOSIVES

Y.P. Samarin, N.I. Sytchev

Samara State Technical University, Samara, Russia

An approximate model of high-speed throwing of convex metal shells which are throwing by a layer of the explosive of variable thickness at arbitrary disposition of the initiation point on the explosive surface is suggested on the basis of theoretical and experimental data.

The first stage of the model consist of the calculation of field velocity on the middle surface of the shell. This calculation takes into account the angle between the detonation wave front and the shell, non-simultaneous loading of different shell elements depending on the initiation point (delay), and also on the density and thickness of the shell and the explosive layer.

An important special case of throwing and deformation of axially symmetric shell with initiation point on the symmetry axis of explosive charge is discussed further in detail.

Necessary cinematic-geometrical conditions at which large deformations of shell are completed by the formation of high speed compact metal mass have been formulated.

These condition are:

a) the mode of metal flow in tangent plane to the deformed surface of the shell,

b) the focusing condition of shell metal into the central part of the forming body.

The presence or absence of cumulating in the deformation in regulated by special inequalities /1 /.

Experimental explosive devices are worked out within the limits of this approach. They enable to fulfill throwing of the shells with the mass up to 10 kg; in this case the mass of the explosive was about 50 kg and the throwing velocity was 1600...1800 m/s.

1. Y.P.Samarin, N.I.Sytchev, Radial deformation of cylindrical shell under the action of detonation products, International Conference SHOCK WAVES IN CONDENSED MATTER, St. Petersburg, Russia, September 2-6, 1996, p.58.

MODEL OF DIFFACTION OF DETONATION WAVES ON CORNER BOUNDARIES IN THICK HIGH EXPLOSIVES

I.F.Kobylkin, O.P.Minin, N.I.Nosenko, V.S.Solovjev

Moscow State Technical University, Moscow, Russia

Corner boundary rounding of detonation waves or sudden changes of propagation direction is accompanied by so called corner effect-occurrence of "dark" zones consisting of high explosives unreakted either completely or partially. The results of experimental investigation and numerical modeling diffraction of detonation waves on corner boundaries in think plate plastic HE are presented in this paper.

Configuration and size of "dark" zones have been determined in the 50*100 mm HE charges 1.8...3 mm thickness. The initiation of diffracting wave has been obtained by using of tape charges 20 mm wide. It is founded that account must be taken of corner effect for a "dark" zone depends on the form and position of detonation wave moving to corner boundary. It is defined by ultra-fast raster photoregistration, that the curvature radius of the detonation front decreases along the detonation wave and has a minimum at the boundary of the dark zone - line of failure of detonation, were it approximated the critical curvature radius R_4cr_0 depending of HE charges thickness and detonation ability. The method of experimental determination of Rcr described. Based on the test data generalized model of diffraction of detonation waves at the corner boundary has been developed.

1) Every element of the diffracting detonation front is considered as a center of the secondary cylindrical (spherical) detonation waves, their velocity are determined from the local curvature of the segment.

2) The envelope of these secondary waves is the detonation front at every succeeding instant, if its curvature exceeds the critical one.

3) In the regions were envelop curvature is less than the critical value is no detonation in them.

The base of the model is an equation of acceleration of detonation front element in normal direction. Together with kinematic surface conditions and geometrical balance conditions in differential form it consists the system of equations in private derivatives. This system describes evolution of leading shock of detonation wave in HE charges. D(h) relation using in this model can be deduced by integrating ordinary differential equation. Its coefficients deduced by simple 1-D trying experiments. In at any case D (h) depends of initial chemical destruction rate and boundary conditions. This model realized in 2-D and 3-D schemes by "wave tracking" method. Numerical modeling of diffraction of angle by detonation wave and founding of the "shadow" zone process in think late HE charges and experimental results introduced. Presented model allows predicting size of "shadow" zone, geometrical parameters of detonation front and distribution of detonation velocity on front surface at any time.

CUMULATIVE JETS IN MICROCHANNELS OF EXPLOSIVES

A.L.Mikhailov, V.A.Sudovtsov, M.Yu.Tarakanov, M.D.Tarasov, A.I.Tolsmyakov

Russian Federal Nuclear Center-VNIIEF, Arzamas-16, Russia

Gradient optical fibers (OF) are used in the work to measure velocities of jet, formed in microchannel inside plastic high explosive (PHE). The same fibers with outside diameter of 0.125 mm were used to perform blind holes of the same diameter in PHE by "pin". The hole depth was varied from 0.5 mm to 2 mm. In microchannels air was at atmosphere pressure. Some of tests were carried out at pressure decreased to 10^3 Pa. In this case "pin" of PHE was carried out in vacuum. PHE was a mixture of fine-dispersed powder of PETN and polyisobutylene. The moment of detonation wave arrival at free surface, which is the microhole bottom, was determined by sharp drop of light intensity. PHE consisted of layers having thickness of 2 mm, separated with lavsan film having thickness of 5μm between each other. This gave time mark of detonation wave motion inside HE. Special tests showed that such film actually gives no any delays in detonation propagation. The moment of arrival of jet, formed in microchannel, at the OF end was determined by sharp increase of luminescense intensity.

The performed tests showed that in vacuumed channels of HE with diameter of ~0.1 mm and length of 0.5-2 mm jets are formed from explosion products or nonreacted HE, moving with velocity of 15.6 km/s. This is at least twice more than velocity of normal detonation. Jet velocity in channels, filled with air, was a bit lower. Let us note that light brightness reserves were insignificant during measurements. This will allow in future carrying out researches with fibers of less diameter (~10μm) and to approach study of processes, occurred in voids and cracks, formed in heterogeneous HE during their manufacturing and handling.

ЭКСПЕРИМЕНТАЛЬНОЕ И ЧИСЛЕННОЕ ИССЛЕДОВАНИЕ ВОЗБУЖДЕНИЯ ДЕТОНАЦИИ В ОКТОГЕН-СОДЕРЖАЩИХ ВЗРЫВЧАТЫХ ВЕЩЕСТВАХ *

В.П.Ефремов, Г.И.Канель, В.Е.Фортов, А.А.Богач, В.В.Якушев, А.В.Уткин, Д.Н.Садовничий, У.С.Юшков, В.М.Лоборев, В.П.Григал, В.Г.Чистов

НИЦ ТИВ ОИВТ РАН, ИХФЧ РАН, ФЦДТ "СОЮЗ", ЦФТИ МО РФ

Широкое использование октогена в различных устройствах и твердых ракетных топливах определяет интерес к экспериментальным исследованиям и численному моделированию условий возбуждения детонации в таких составах.

В настоящей работе исследовался флегматизированный прессованный октоген с плотностью 1.77 г/см^3. Нагружение исследуемых образцов производилось ударом плоских алюминиевых ударников, разогнанных продуктами детонации. Регистрация профилей давления осуществлялась с помощью манганиновых и ПВД-датчиков расположенных в различных сечениях исследуемых образцов. Полученные результаты моделировались с использованием двухмерного гидродинамического кода. Проведенные расчеты и их сравнение с экспериментальными данными позволили определить константы в кинетике энерговыделения. Часть тестируемых образцов перед нагружением облучали непрерывным g-излучением до доз в интервале от 2-х до 25Мрад. Структура образцов до и после облучения анализировалась с ипользованием электронной микроскопии. Полученные данные по изменению ударно-волновой чуствительности в результате облучения сравниваются с результатами испытаний образцов литых ВВ до и после облучения.

(* *Experimental and Numerical Study of Detonation Initiation in HMX Based Explosives,* V.P.Efremov, G.I.Kanel, V.E.Fortov, A.A.Bogach*, V.V.Yakushev*, A.V.Utkin*, D.N.Sadovnichy**, E.S.Ushkov**, V.M.Loborev°, P.V.Grigal°, V.G.Chistov° High Energy Density Research Center, Moscow; * Institute of Chemical Physics, Chernogolovka; **Federal Center of Double Technologies, Moscow; °Central Institute of Physics and Technology, Sergiev Posad, Russia)

О РАЗЛОЖЕНИИ ПОРИСТОГО ГЕКСОГЕНА В ШИРОКОЙ ОБЛАСТИ УДАРНО-ВОЛНОВЫХ ВОЗДЕЙСТВИЙ*

К.К.Шведов

Институт проблем химической физики, Черноголовка, Россия

К настоящему времени получено много данных, дающих веские доказательства тепловой природы химического разложения взрывчатых веществ (ВВ) в ударных и детонационных волнах. Однако не ясно, в какой мере кинетические закономерности термического разложения ВВ при нормальном давлении и развитые на их основе представления можно переносить на условия ударно-волнового нагружения. Для ответа на этот вопрос представляют интерес данные о разложении, полученные на одном и том же объекте в широком диапазоне динамических давлений.

В работе обобщены результаты исследований разложения пористого гексогена (плотность заряда 1.0 г/см^3) различной дисперсности в области динамических давлений от 1 до 20 ГПа. Показано, что при низких давлениях ударной волны (1-2 ГПа) время разложения, определенное по газодинамическому эффекту торможения границы раздела инерт-ВВ, существенно зависит от амплитуды и размеров частиц ВВ. При этом оно может быть описано формально - кинетическими зависимостями, подобными для термического разложения ВВ при нормальном давлении. При увеличении амплитуды ударной волны и сжатии исходного вещества во фронте до плотности монокристалла (P≈6,0 ГПа) происходит качественное и количественное изменение закономерностей разложения. В области давлений выше 6,0 ГПа разложение вещества происходит по механизму адиабатического теплового взрыва, время реакции, определенное по газодинамическому эффекту торможения или "химпику" в стационарной детонации, практически не зависит от амплитуды волны, исходных размеров частиц ВВ, наличия и свойств наполнителя.

Полученные результаты объясняются на основе представлений о тепловой природе воспламенения и разложения гетерогенных ВВ с учетом специфики ударно-волновых воздействий.

(* *On Decomposition of Porous RDX with a Wide Range of Shock Wave Impact,* K.K.Shvedov, Institute of Chemical Physics, Chernogolovka, Russia)

К ВОПРОСУ О ВЛИЯНИИ ПЛОТНОСТИ НА ПЕРЕХОДНЫЕ ПРОЦЕССЫ ПРИ УДАРНО–ВОЛНОВОМ ИНИЦИИРОВАНИИ *

С.А.Колдунов

Институт проблем химической физики, Черноголовка, Россия

Многочисленные данные свидетельствуют, что присутствие пор (пористость) оказывает существенное влияние на результат ударно–волнового воздействия. Наиболее наглядно это проявляется во влиянии на чувствительность к ударным волнам начальной плотности порошкообразных энергетических материалов. В частности, в стандартных испытаниях на чувствительность по схеме "активный заряд – инертная преграда – пассивный (испытываемый) заряд" предельные толщины преграды, которые еще обеспечивают возбуждение детонации в пассивном заряде, всегда больше при насыпной плотности. Выполненные ранее автором исследования эволюции в переходной области профиля массовой скорости инициирующих ударных волн (ИУВ) показали, что имеет место определенное отличие также и в характере развития энерговыделения за фронтом УВ в зарядах насыпной плотности и в плотных прессованных. В последних максимум энерговыделения достигается на некотором удалении от ударного фронта (переходный профиль с "горбом"). В то время как в насыпных зарядах энерговыделение протекает всегда более интенсивно непосредственно за фронтом ИУВ (переходный профиль спадающий). Очевидно, должен существовать некоторый уровень по плотности (ρ_0*), достижение которого приводит к изменению в режиме энерговыделения за фронтом УВ. В работе предпринята попытка получить экспериментальные доказательства высказанным соображениям. Для этой цели использовались заряды из молотого тротила, плотность которых охватывала диапазон $1 г/см^3 < \rho_0 < 1{,}59$ $г/см^3$. Образцы нагружались от взрывных генераторов УВ, которые обеспечивали соответствующие ударно-волновые воздействия, максимально приближенные к предельным для развития детонации.

Данные об изменении исходного (близкого к треугольному) профиля массовой скорости ИУВ получены на начальной стадии распространения УВ в исследуемых зарядах, которая характеризуется постоянством (слабым изменением) параметров фронта. Именно на этой стадии переходного процесса должны проявлять-

ся отличия в характере эволюции профиля ИУВ в зависимости от плотности порошкообразного заряда. Для исследуемых зарядов тротила было установлено, что уровень плотностей 1,4 ÷ 1,41 г/см^3 отвечает тем граничным значениям ρ_0*, ниже которых ударная волна в процессе развития в детонационную сохраняет спадающий профиль. В то время как при плотности не ниже 1,41 г/см^3 стадии ускорения УВ всегда предшествует формирование переходного профиля с "горбом". Интересно отметить, что найденным значениям ρ_0* отвечает уровень пористости, ниже которого начинают преобладать закрытые поры.

Представляется, что данные по ρ_0*, определенные для различных веществ, позволят более обоснованно судить о механизме процессов, ведущих к образованию и развитию очагов превращения (горячих точек) при ударном сжатии порошкообразных сред. Более конкретный смысл в понимании и моделировании таких процессов должны приобрести в этой связи данные о характере и уровне пористости, размере зерна, свойств собственно вещества и т.д. Эти вопросы, а также вопросы, затрагивающие влияние начальной плотности на пределы возбуждения и распространения детонации, предлагаются к обсуждению.

(* To the Density Effect on Transition Shock Initiation Processes, S.A.Koldunov, Institute of Chemical Physics, Chernogolovka, Russia)

INFLUENCE OF SOLID CARBON PHASE TRANSITIONS ON DETONATION PARAMETERS OF HIGH EXPLOSIVES: ANOMALOUS MODE OF DETONATION

S.B.Victorov, S.A.Gubin

Moscow State Engineering Physics Institute (Technical University), Russia

Condensed carbon presents in detonation products of many high explosives (HE). Its principal phase states are graphite, diamond and liquid. Carbon phase state in detonation products depends on their temperature and pressure and affects to detonation parameters of explosives because distinct carbon phases have different thermodynamic properties. Therefore, knowledge of carbon phase state in detonation products is important for accurate prediction of HE detonation characteristics.

We have researched the detonation properties of carbon-rich TNT and carbon-poor RDX to show how changes of carbon phase state in detonation products influence HE detonation parameters.

Besides different carbon content several other factors motivate the study of these two explosives. There are a lot of precise experimental data on detonation parameters of TNT and RDX. Hence, it is possible to compare calculated detonation parameters with experimental ones. Both explosives have breaks in their experimental dependencies of detonation pressure and velocity on initial charge density. These breaks seem to be result of phase transitions in the detonation products. Thus, the choice of TNT and RDX for studying effects of carbon phase transitions on HE detonation behavior is quite justified.

A new computer code (TDS) has been developed to carry out multi-phase equilibrium calculations of HE detonation. The TDS code allows to determine all local minima of thermodynamic potentials of detonation products and to find the only point of the HE Hugoniot which corresponds to the real state of products behind the detonation wave.

The Hugoniots of TNT and RDX were carefully researched by means of the TDS code. The size and structure effects of graphite and diamond crystals were taken into account. New equations of state were used for graphite and diamond to describe thermodynamic properties of solid carbon phases more accurately.

Previous theoretical investigations of TNT detonation associate a break in the detonation velocity D vs ρ_0 slope at initial charge density $\rho_0 = 1.55$ g/cm^3 with the graphite to diamond transition and assume that both phases of solid carbon (i.e. graphite and diamond) are present in the TNT detonation products at $\rho_0 \geq 1.55$ g/cm^3.

Our researches confirm that this break in the D vs ρ_0 slope is really caused by the graphite to diamond transition but the assumption about graphite-diamond coexistence in the detonation products was found to be quite incorrect.

In fact, coexistence of both the graphite and diamond phases of solid carbon in detonation products of the considered explosives is impossible at any ρ_0. Depending on ρ_0, the condensed detonation products consist of either graphite (at $\rho_0 < 1.55$ g/cm^3) or diamond (at $\rho_0 \geq 1.55$ g/cm^3). Both explosives have a range of ρ_0 ($1.55 \leq \rho_0 < 1.65$ g/cm^3 for TNT and $1.55 \leq \rho_0 < 1.6$ g/cm^3 for RDX) where their detonation occurs in an anomalous mode: the CJ condition of equality between sound velocity and velocity of detonation products is not satisfied but

the detonation is stable. Our calculation predicts sharp increase of temperature and pressure of the detonation products and break in the D vs ρ_0 slope at the beginning of "anomalous region" of ρ_0 (i.e. at ρ_0 = 1.55 g/cm^3 for both considered explosives). The calculated detonation properties of TNT and RDX fit available experimental data.

The anomalous mode of detonation exists due to the following difference between graphite and diamond thermodynamic properties: at the same temperature and pressure entropy of diamond always appears less than entropy of graphite. At some HE initial densities this feature of carbon thermodynamics causes solid carbon to change its phase state in the detonation products (graphite to diamond transition occurs) and results in appearance of the anomalous detonation.

We have shown why the anomalous mode of detonation is stable in spite of the CJ condition failure.

The anomalous detonation seems to be "the rule rather than the exception" even for explosives containing relatively small amounts of carbon. We expect that many high explosives have a range of initial charge densities where their detonation occurs in the anomalous mode.

ЧУВСТВИТЕЛЬНОСТЬ КОНВЕРТИРУЕМЫХ БАЛЛИСТИТНЫХ ПОРОХОВ К УДАРНОЙ ВОЛНЕ *

О.А. Исаева, А.Н.Афанасенков[1], В.В. Галкин

НИИ Центр "КАСТЛ"; [1]Институт химической физики, Черноголовка, Россия

В последнее десятилетие в связи с конверсией ряда отраслей оборонной прмышленности высвобождается значительное количество баллиститных порохов (артиллерийских, ракетных). Отимальный путь их утилизации - это использование их во взрывном деле в качестве водостойких ВВ или как компонентов новых промышленных ВВ. Поскольку пороха относятся к метательным составам, то использование их в качаетве ВВ предопределяет всестороннее изучение их детонационных и взрывчатых характеристик, чувствительности к средствам инициирования. Для того, чтобы взорвать заряд баллиститного пороха, надо иметь достаточно надежный инициатор (боевик), выбор которого облегчается, если известна чувствительность пороха к ударной волне. Этому вопросу и посвящена работа авторов.

Исследовалось несколько видов баллиститных порохов в сплошном состоянии. Опыты по определению чувствительности

пороха к ударной волне, которая характеризовалась критическим давлением инициирующей ударной волны (Ркр), проводились по известной схеме: активный заряд - инертная преграда - заряд пороха. В качестве активных использовали заряды тротила разной плотности, в качестве преграды - медная пластина толщиной 5 мм, все диаметром 40 мм. Используя зависимость давления ударной волны на выходе из преграды от плотности зарядов тротила и ударную адиабату пороха, которая для всех порохов записывалась в виде единой обобщенной зависимости $D=1,73+2*U-0,1*U^2/1,73$ (км/сек), были определены величины Ркр для 6-ти баллиститных порохов (диаметр заряда 40 мм). Величина его колеблется от 5,8 ГПа для пороха РСТ-4К до 8,6 ГПа для пороха НБ-40. Таким образом, баллиститные пороха имеют чувствительность к ударной волне меньшую, чем прессованные бризантные ВВ, но большую, чем жидкие ВВ. Для порохов НБ-40 и РСТ-4К определены зависимости Ркр от диаметра заряда. С ростом диаметра заряда величина Ркр уменьшается.

* *Sensitivity of Gun Powder to Shock Wave Action,* O.A.Isaeva, A.N.Afanasenkov*, V.V.Galkin ("Kastl" Research Center, Moscow; *Institute of Chemical Physics, Chernogolovka, Russia)

КРИТИЧЕСКИЕ ДИАМЕТРЫ ДЕТОНАЦИИ РАСТВОРОВ ВЗРЫВЧАТЫХ ВЕЩЕСТВ

Воскобойников И. М, *Душенок С. А., *Котомин А. А.

Институт химической физики РАН, Москва,
СКТБ "Технолог", С. - Петербург

Исследование изменений критических диаметров детонации жидких взрывчатых веществ при разбавлении разными растворителями помимо решения некоторых практических задач, связанных с хранением и транспортировкой продуктов, обещает получение дополнительных сведений о макрокинетике превращений в детонационной волне. Из-за однородности жидкости (исключаются из рассмотрения низкоскоростные режимы детонации, для распространения которых существенно образование и схлопывание кавитационных полостей, возникающих на стадии инициирования и др.) превращения за ударным фронтом детонационной волны протекают в форме адиабатического взрыва, времена развития которого определяются разогревами в объеме вещества до 1500...2000 К. В работе объектами исследования выбра-

ны растворы бисфтординитроэтилформаля $CH_2(OCH_2C(NO_2)_2F)_2$ (далее ФЭФО), нитрометана CH_3NO_2, изопропилнитрата $CH_3CH(ONO_2)CH_3$ (ИПН), глицеринтринитрата $CH_2(ONO_2)CH(ONO_2)CH_2(ONO_2)$ (НГЦ), 1,6-диазидо-2-ацетоксигексана $N_3CH_2CH(OCOCH_3)CH_2OCH_2CH_2N_3$ (диазид), и пропиленгликольдинитрата $CH_2(ONO_2)CH_2CH_2(ONO_2)$ (ПГДН), а также растворов ФЭФО с этанолом, ацетоном, дибутилфталатом и циклогексанолом.

Критические диаметры детонации d_c растворов в тонкостенных бумажных оболочках, покрытых изнутри полиэтиленом, были определены в общепринятой для таких измерений постановке. Далее были рассчитаны температуры вещества на ударном фронте детонационной волны T_f, соответствующие экспериментальным значениям скоростей детонации растворов. Обнаружено, что близким значениям d_c растворов ФЭФО и НГЦ с нитрометаном, а также растворов ФЭФО с ИПН и ПГДН с нитрометаном отвечают близкие рассчитанные значения T_f. Тем же величинам d_c растворов ФЭФО с диазидом, а также этанолом, дибутилфталатом, ацетоном и циклогексанолом соответствуют несколько большие температуры T_f, которые для этой группы хорошо согласуются между собой. То есть, ведущей стадией протекания реакции за фронтом волны в растворах ФЭФО с нитрометаном и ИПН скорей всего является разложение последних (разложение нитрометана при высоких давлениях происходит в аци-форме с кинетикой близкой к кинетике разложения нитратов спиртов), а для растворов ФЭФО с невзрывчатыми разбавителями и диазидом ведущая стадия реакции связана с разложением ФЭФО.

То, что ведущей стадией превращения за ударным фронтом детонационной волны в растворах ФЭФО с диазидом является разложение ФЭФО, выглядит вполне ожидаемо. При достигаемых температурах около 2000 К рассчитанные задержки адиабатического взрыва ФЭФО при использовании кинетических параметров, найденных для газовой фазы, почти на 2 порядка меньше рассчитанных задержек взрыва диазида. Несколько неожиданно более быстрое разложение в детонационной волне растворов с ФЭФО нитратов спиртов и нитрометана, поскольку рассчитанные при тех же температурах задержки адиабатического взрыва ФЭФО на 1...2 порядка меньше задержек взрыва нитратов спиртов. Это может быть связано с изменением при переходе к столь высоким температурам и давления кинетических параметров, найденных для газовой фазы при температурах 400...450 К. Наи-

более вероятным представляется уменьшение величины предэкспонента в законе Аррениуса, причем для ФЭФО это уменьшение будет на 1...2 порядка большим, чем для нитратов спиртов. Найденные для газовой фазы значения энергии активации мономолекулярного разложения рассматриваемых взрывчатых веществ (ФЭФО, нитратов спиртов) вполне соответствуют наблюдаемым изменениям критических диаметров детонации при разбавлении их невзрывчатыми компонентами.

Макрокинетика деструкции жидких ацетона, дибутилфталата и спиртов за фронтами ударных волн не исследовалась, но существенно, что рассчитанные температуры за ударными фронтами детонационной волны в растворах ФЭФО выше температур, приводящих к деструкции использованных разбавителей за ударными фронтами. Особенно это относится к ударно-волновому сжатию ацетона и дибутилфталата, что могло найти отражение в макрокинетике превращения за ударным фронтом волны в растворах ФЭФО в целом. Однако полученные в работе данные об изменении критических диаметров детонации растворов ФЭФО с инертными разбавителями удовлетворительно объясняются и без предположения о более быстром, чем ФЭФО, разложении ацетона и дибутилфталата.

Количественные изменения критических диаметров детонации растворов ФЭФО, нитрометана и нитратов спиртов, как и соотношение величин критических диаметров детонации более десятка нитратов спиртов различного состава удается с хорошей точностью предвидеть в предположении пропорциональности величины d_c произведению скорости детонации на характерное время превращения за ударным фронтом волны.

THERMAL DECOMPOSITION OF ENERGETIC MATERIALS

S. Almada*, J. Campos ** and J.C. Góis**

*Laboratory of Energetics and Detonic, * Naval Explosives Laboratory, Alfeite - 2800 Almada*

***Mech. Eng. Depart. - Faculty of Sciences and Technology-*

Polo II - University of Coimbra - 3030 COIMBRA - PORTUGAL

Knowing the thermal behaviour of energetic materials is crucial to a safe production, storage, handling or even demilitarisation. The studies necessary to quantify the thermal decomposition mechanisms and kinetic, are usually

complex and an extrapolation to real scale could not be acceptable. To obtain more accuracy and because many energetic materials are heterogeneous, we need to made tests with a scale higher than the classic methods but limited because safety and costs.

An original equipment was developed based in a burner fed with a mixture of propane/air and a glass column above which the sample, up to 500 mg, is placed. For a predetermined heating rate, temperature and weight variations were measured in order to time. With this equipment it was possible to characterise the behaviour after thermal initiation: combustion or explosion of different energetic materials. This has been useful to estimate the ignition temperature and delay and the kinetic parameters.

The materials selected were, for being typical cases, ammonium nitrate (AN), pentaerythritol tetranitrate (PETN), hexogen (RDX).

The developed equipment was validated with the matching results from classic termogravimetric analysis (DSC and TGA), with the kinetic approach of Coats and Redfern. With this non-isothermal method, the activation energy and pre-exponential factor were 2.10×10^{5} J mol^{-1} and 2.38×10^{17} s^{-1} for AN, 1.16×10^{5} J mol^{-1} and 1.17×10^{19} s^{-1} for PETN and 1.10×10^{5} J mol^{-1} and 4.95×10^{12} s^{-1} for RDX.

In spite of the equipment limitations the obtained results were compared with those from some other authors and seem to bee very concordant. Heterogeneous energetic materials need to be tested for each lot, so, we need cheaper ways to do it. With the equipment developed in the present work it will be possible to study those energetic materials, with lower costs.

SHOCK SENSITIVITY OF A NEW PROPELLANT FORMULATION BASED ON PHASE STABILIZED AMMONIUM NITRATE (PSAN), 2-OXY-4,6-DINITRAMINE-S-TRIAZINE (DNAM) AND HYDROXY TERMINATED POLYBUTADIENE (HTPB)

P. Simões, L. Pedroso, *I. Plaksin, *J. Ribeiro, A. Portugal and *A. Campos

*Lab. of Energetics and Detonics, Chem. Eng. Dep., *Mech. Eng. Dep.,*
Fac. of Sciences and Technology, University of Coimbra,
3030 COIMBRA, Portugal

Efforts are being made to overcome the environmental problems posed by the classic propellants based on Ammonium Perclorate (AP). In some kind of applications, the possible replacement of AP by Ammonium Nitrate or its Phase Stabilised forms (PSAN) is matter of interest. Besides its low pollutant characteristics, PSAN presents low

cost, good chemical stability, and low energy and low sensitivity to shock. However, some drawbacks are to be accounted, being the low energy and low reactivity a limiting feature of PSAN in its use as the unique oxidiser component in propellant formulations.

The compound 2-oxy-4,6-dinitramine-s-triazine (DNAM) was synthesised and characterised, and its use as an additive in PSAN/HTPB based propellants has shown good potential regarding the combustion characteristics. As far as possible, an increase in the combustion behaviour should be attained without expenses in the sensitivity to shock of the global formulation. Thus, the knowledge of the shock sensitivity is of prime importance when a new propellant formulation is under study.

This work is the study to the shock sensitivity of propellant based on a mixture of PSAN and DNAM as the solid oxidiser load and HTPB as the binder systems. The used propellant formulation for this study was 68 wt % PSAN, 12% DNAM and 20% HTPB. The PSAN and DNAM have respectively a medium crystal dimension d_{50} =140 μm and d_{50} = 5 μm . The propellant density is 1.33 .10^3 kg/m3, corresponding to 90% of its TMD.

The samples of the propellants with the dimensions 30 x 15 mm were tested. The explosive plane wave generators were used for the shock loading of the samples, allowed the input the sustained shock waves amplitude of 1 to 10 GPa, and with 1-2 μm of duration in the stationary part of P(t). The process of shock wave propagation into the samples has been registrated quasicontinuously, through each 200 μm, by thin multifiber optical strip, consisted of 80-90 independent channels, and connected directly to a fast electronic streak camera (Thompson 506 TSN).

The analysis of the registrated (x-t) diagrams of shock wave propagation, into the samples, allows to evaluated the non reactive or reactive behaviour, for the proposed propellant. The obtained results show the new propellant composition as an essentially less sensitive propellant to the shock loading, by the comparison with classic propellants based on AP.

SESSION "Numerical Modeling of Detonation Processes"

Co-Chairmen:
V.Klimenko - Institute of Chemical Physics, Moscow, Russia
C.Coffey - Naval Surface Warfare Center, USA

OVERVIEW AND ANALYSIS OF NUMERICAL DETONATION MODELS

V.Yu.Klimenko

High Pressure Center, Institute of Chemical Physics, Moscow, Russia

Tremendous progress in a computer technique changes qualitatively a situation in shock wave science. In the 60-80 years the experiment dominated in our investigations. However, by now the computer simulation becomes a powerful tool in the study of shock wave phenomena. The numerical experiment (instead of the real physical experiment) gives an unique possibility to discover the interior deep mechanisms of explosion processes that are inaccessible for the existing experimental technique.

For example, a very old problem of the pore collapse in explosive under shock compression and the creation of hot spot. It is a very complex process. The pore is very small (~ 1 μm), the time duration of the process is also small (~ 0.1 μs) and the explosive is opaque. Clearly that any experiment can not indicate in detail this process. But, the computer simulation [1] has permitted to discover and to analyse a physical nature of the pore collapse comprehensively. Or the another example. The explosive initiation by the projectile is very important for practice. But, until now the physical mechanism of the initiation process in critical conditions has not been studied. Many years many researchers studied this process both experimentally and theoretically and have established some criterions of initiation, but the interior physical nature has not been determined. Only recently the careful numerical simulations [2] have given the detailed information about the mechanism of this very complex process.

However, the simulations will be most important and successful for applied developments, for design of new engineering systems.

Thus, by 2000-2002 years we shall have the supercomputers with performance 10-100 Teraflops. It means that at last we receive a possi-

bility to simulate physical and chemical processes in explosives, metals and another materials with great resolution (i.e., to use a fine numerical grid). If, for example, we apply the adaptive gridding procedure with mesh size from 0.01 mm to 1 mm, than we can simulate real engineering systems (size = 10-100 cm) and use the fine zoning (~ 0.01 mm) for most important computational regions (shock fronts, interfaces, large gradients in some physical parameters).

In this case (the mesh size ~ 0.01 mm) we can simulate the real reaction zone for detonation process and use for this the perfect physical models of detonation with high accuracy. So, it is not necessary to apply the empirical (not physical, but mathematically approximated) detonation models (for example, very famous WBL [3] and DSD [4] models) for such calculations, because these models have low accuracy and can not simulate exactly the complex detonation processes (for example, shock-to-detonation transition or two-step shock compression). Before preparation of the physically perfect model it is necessary to analyse the existing models and to outline a strategy for such activity.

Present report represents overview and analysis of the existing numerical models of detonation that are constructed on the basis of physical processes occurring in explosive during detonation.

In the first part we give the overview of the physical mechanisms that have been discovered by now. This is well known hot-spot mechanism, i.e.. the collapse of pore in explosive, the viscoplastic heating of the explosive layer around the pore and decomposition of this heated explosive. At the beginning the mechanism was studied in some classical investigations [5-7]. but most successful and comprehensive consideration is given in the work [1].

We also discuss the frontal mechanism that was first proposed in 1980 [8] and was developed in the next papers (for example, [9,10]). The mechanism has two stages: intra-frontal and post-frontal. The intra-frontal stage proceeds in a shock wave front and its governing process is the temperature overheating. Radicals are generated at this stage. At the second stage they start up a some set of consecutive-parallel reactions that results in final products with corresponding energy release.

At last we consider the dislocation mechanism [11]. High rate plastic deformation of explosive goes through the generation and motion of dislocations. The mechanism has two modes. At low pressure moving dislocations create overheated microregions and these heated spots generate hot spots. At high pressure when the dislocations have enough large velocity they generate phonons of sufficient energy for

resonant excitation of the vibrational modes of explosive molecule. These excited molecules decompose and activate the later decomposition of surrounding explosive. But, it is possible to propose some new mode for dislocation mechanism. Under dislocation motion two molecules in the core of dislocation slip one through other at small distance and create conformational conditions for bimolecular reaction which proceeds during this slipping contact.

The hot spot, frontal and dislocation mechanisms act together, i.e., in parallel regime. But, the hot spot mechanism dominates in the low pressure region and the frontal mechanism - in the high pressure region. This multiprocess idea was first proposed in 1988 [12].

When we discuss the mechanism of detonation we must take into account the explosive class. From the point of detonation mechanism it is possible to separate the standard applied explosives (explosive compositions) into three classes. The first class represents explosives prepared by pressing without any binder. As usually they have high porosity (5-10%). The second class is the explosives pressed with binder (about 5 %). They have low porosity (about 1%). It is so named PBX explosives. The third class - the cast explosives with big fraction of plastic binder (as usually 20-30 wt % or 30-40 vol %). They have not any porosity.

The second class of explosives is a kind of standard for development of detonation models. Here the hot spots mechanism dominates at low and middle pressures (P=20-150 kbar).

The frontal mechanism dominates at high pressures ($P > 150$ kbar). At very low pressures ($P < 20$ kbar) only the dislocation mechanism can provide for the effective decomposition of explosive.

In the first class of explosives the porosity is large and the shock front is smoothed in the most part of explosive volume. The more porosity, the more decreasing the action of the frontal mechanism (i.e., the more small part of explozive is treated by the front). So, the hot spots mechanism dominates in large part of pressure region.

The explosives of the third class have zero porosity. Pores (of normal size that can reply to shock compression) are absent and the hot spots mechanism does not work. Here the dislocation mechanism dominates at low and middle pressures. At high pressures the frontal mechanism intercepts initiative.

For deep understanding of physical nature of the detonation process it is extremely important to investigate detonation in liquid and melted explosives. Clearly that in this case the hot spots and dislocation mechanisms do not work, and only the frontal mechanism acts.

However, it is necessary to remember that the frontal mechanism operates if the explosive molecules are enough large and therefore the frontal effect (i.e., the temperature overheating) is turned on.

For liquid explosives with small molecules, e.g., nitromethane, we can observe creation and growth of hot spots at low pressures (F.Walker, R.Wasley - 1976, A.Vorobiev, V.Trofimov - 1980) . These hot spots are generated at microlevel by interaction of shock wave front with the fluctuations of density. The three-stages mechanism (developed on the basis of the molecular dynamics simulations [13]) describes this process in details.

In the second part of the present report we give overview and analysis of the most famous existing numerical models of detonation. In the beginning we consider the hot spots models: the Ignition and Growth model [14,15], the Explicit Hot Spot model [16], the Kim's model [17] and the AMORC model [18]. Next we discuss the Multiprocess model [9,10]. Finally we analyse the predictive performance of the discussed models and consider the possibilities for preparation of the physically perfect model of detonation.

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NUMERICAL SIMULATION OF TATB DETONATION BY A SHORT PRESSURE PULSE AT THIN PLATE IMPACT

V.G.Morozov, I.I.Karpenko, L.V.Dmitriyeva, N.V.Korepova

Russian Federal Nuclear Center-VNIIEF, Arzamas-16, Russia

Up to the present a shock wave transition to a detonation wave has been studied within the model of detonation kinetics [1, 2] for quite long effects of a pressure pulse. The shortest pressure pulse effects numerically simulated with account of kinetics are TATB explosive loading by the impact of steel plates two millimeters in thickness accelerated to velocities 1.9 - 2.4 mm/μs [1].

The problem of kinetics model use for more short pulses seems very interesting and important. The series of computations on numerical simulation of the experiment described in paper [3] has been conducted. A stationary detonation wave forming by a short pulse due to TATB-based HE impact on a flying plate made of mylar 0.051mm - 1.27 mm thick and accelerated to high velocities 3.4-8.2 km/sec by the electrical explosion of aluminum foils has been studied there. Using

flying plates of different thickness one may obtain an initiating pulse in a wide range of applied pressures and durations. The data we used for simulations are referred to a TATB-based HE containing 7.5% of Kel-F plasticizer and compressed up to the initial density 1.90 g/cm3.

Setting of computations is described in details in the paper which results are in good agreement with the experiment.

Delay times and depths of detonation occurrence at short pulses, namely, at the TATB-based HE impact by thin films (0.0051-0.127 cm) of a small initial density 1.2 g/cm3 accelerated to velocities 3.4-8.2 km/sec by aluminum foil explosion are determined.

Popolato computational diagrams are obtained. Computations and plots given in the paper demonstrate the mode of transition from damping detonation to a stationary detonation wave forming in PBS at short pulses. The dependence of a minimal velocity at which stationary detonation is initiated on a flying plate thickness is found computationally. Experimental points laid quite well on calculated curves.

Result convergence studies are conducted and optimal conditions (spatial step, mass relations in computational cells at material interfaces) for the given class problems are obtained.

One may conclude that the kinetics model [1, 2] may be used without adjustment for detonation modeling at short pulses.

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THE STEADY SOLUTION OF A REACTION ZONE STRUCTURE ON THE PLANE DETONATION WAVE

Yu.A.Aminov, N.S.Es'kov, Yu.R.Nikitenko, G.N.Rykovanov

Russian Federal Nuclear Center-VNIITF, Chelyabinsk-70, Russia

The comparative analysis of applicability of various decomposition models for the description of reaction zone structure is presented. The behavior of reacting explosive parameters are determined by a numerical method on the basis of solution of a algebraic equations system together with the given law of explosive decomposition and equation of state for a initial explosive and the reaction products. The algebraic equations connecting the parameters of explosive and the reaction products are obtained by integration of a gas dynamics differential equation system. The plane detonation wave in heterogeneous solid explosives is considered.

Most of semiempirical decomposition models were calibrated by means of experiments with non-steady detonation and satisfactorily describe processes of initiation and growth of detonation under shock loading [1 - 4]. For some models it is shown that calculated space profiles of the pressure do not correspond to theoretical concept and experimental data. Used experimental profiles are determined by photoelectric technique [5] based on the recording of shock front radiation in indicating liquid. Some explosives based on HMX, RDX, TNT and TATB are considered.

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FEATURES OF DETONATION INITIATION IN GAP TESTS

Yu.A.Aminov, N.S.Es'kov, O.V.Kostitsyn, G.N.Rykovanov, M.A.Strizhenok

Russian Federal Nuclear Center-VNIITF, Chelyabinsk-70, Russia

Gap tests are often used to study explosives sensitivity to weak shock waves. The experimental setup consists of an active charge, a PMMA barrier and a passive charge made of the studied explosive. The active charge is point-initiated at the center. The intensity of initiating shock wave can be varied by varying the barrier thickness. The average velocity of the shock or detonation wave in the passive charge is determined experimentally.

Numerical simulation of the experiments on a plastic bonded TATB-based explosive (PBT) revealed that at the barrier thickness near to the critical quantity the region where the detonation start has a ring-shaped form. For a 60 mm diameter, 20 mm thick HMX-based active charge the initial diameter of this region was found to be about 50 mm. The simulation was performed using the two-dimensional MAX code [1] and the one stage semiempirical detonation model [2], based on the hot spot hypothesis and having a small number of parameters. The basic feature of the model is the smooth transition to the Arrhenuis kinetics at shock pressures above a critical level. Using this model a number of experiments on detonation initiation of PBT by plane, cylindrical and spherical shock waves were successfully described.

We use quality reasons to explain this phenomenon. The detonation initiation is determined by amplitude and duration of shock loading. In a considered case the normal fall of shock wave at barrier center smoothly passes into slipping regime in a distant area. At some distance from an axes the pressure profile of shock wave entering the barrier becomes less sharp and its weakening by a barrier decreases due to increasing of a front curvature. Therefor entering PBT shock wave has more flat pressure profile at this area and a time of the big shock loading is increased. At some barrier thickness the amplitude of a shock wave can appear here more than in a center zone. In this case the PBT decomposition can arise here even if it do not be in a center zone.

The special experiments were carried out for studying a real PBT decomposition picture in such systems. The facility diameter was increased up to 120 mm to simplify a realization of phenomenon. The ac-

tive charge thickness was H_a=20 mm. Photochronograph technique was used for registration of the output time of a detonation wave front on a free PBT back. The PMMA thickness was selected to make critical conditions of detonation initiation. At a PBT sample thickness H_{PBT}=60 mm delay of a detonation wave front was $\Delta t \sim 2$ μs in the center of back. Thus, the experimental confirmation of emergence of the ring-shaped decomposition location in considered experiments is obtained at critical conditions on detonation excitation. The calculation results by MAX for H_{PBT}=60 mm are in agreement with experimental data.

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EQUATION OF STATE OF THE HETEROGENEOUS MIXTURE WITH THE UNREACTED EXPLOSIVE AND ITS REACTION PRODUCTS IN THE REACTION ZONE OF THE DETONATION WAVE, CRITERION OF DETONATION FOR THE PLANE GEOMETRY AND TRANSITION TO DETONATION

Y.W.Kuzmitskii

Russian Federal Nuclear Center - VNIIEF, Arzamas - 16, Russia

The reaction zone matter of the steady wave or transition to detonation is a heterogeneous mixture of unreacted explosive (subscript "$_1$") and its reaction products (subscript "$_2$") . The equation of state for such a mixture constructed of those of the fraction in the form:

$$\varepsilon(\rho_1,P_1,\rho_2,P_2,F)=(1-F)*\varepsilon_1(\rho_1,P_1)+F*\varepsilon_2(\rho_2,P_2) \quad (1)$$

where F is a reacted fraction and both $\varepsilon_1(\rho_1,P_1)$, $\varepsilon_2(\rho_2,P_2)$ are equations of state of unreacted explosive and its reaction products, accordingly. The mixture density ρ is usually found as a sum of the reacted and unreacted volumes:

$$1/\rho = (1-F)/\rho_1 + F/\rho_2 \quad (2)$$

The following simplifications relate to the approximation $P_1 \approx P_2 \approx P$, that is justified by a fine heterogeneous mixture of reacted and unreacted material, so that their pressures is approximately equal to each

other . The new approximation is that for fractions of density a similar relation takes place :

$$\rho_1 \approx \rho_2 \approx \rho \quad (3)$$

This fact must be clear after differentiation with respect to time of equation (2):

$$(\rho_2-\rho_1)^* \partial F/\partial t = \{((\rho_1^*\rho_2)/\rho^2)^* \partial\rho/\partial t - (\rho_2)/\rho_1)^* \partial\rho_1/\partial t - (\rho_1)/\rho_2)^* \partial\rho_2/\partial t\} \quad (4)$$

Any changes in densities of all of the unreacted explosives, their reacted products and mixture must be slower than the reaction rate $\partial F/\partial t$. So, we have equation (3) in the limit $\partial F/\partial t \to \infty$. Thus, the equation of state of the heterogeneous mixture depends on three quantities:

$$\varepsilon(\rho,P,F)=(1-F)^* \varepsilon_1(\rho,P) +F^* \varepsilon_2(\rho,P) \quad (5)$$

Equation (3) was validated by the comparison with precision selfsimilar solution for the steady detonation wave structure at $\rho_1 \neq \rho_2$ and the approximate solution where these densities are equal, as in equation (3). The departure of the approximate solution curve from precision selfsimilar one versus fraction of the reacted matter at F = 0...0.8 is less than 2% and at the final stage of burn will be greater reaching ~ 15% at F = 1.0. The total influence on the length of the reaction zone is less than ~ 4.9%.

With this equation of state for mixture the problem of the initiation criterion was considered for detonation with a plane one-dimension flow in the heterogeneous TATB formulation. The initiation was carried out using thin flyers of various thicknesses at appropriate data for the velocities. A "Juge mobility point" and a "Critical point" conception was proposed. A new SHOCK INITIATION CRITERION of detonation was postulated with both of them :

After the initiating shock front transition to detonation the Juge mobility point is generated at critical reaction fraction F_{KR}, but at the same time the front pressure falls down to critical P_{KR} and the reaction is suppressed completely.

This criterion with the reaction rate and the equation of state JWL (LLNL, 1995) for a TATB explosive was used for the calculations of a critical thickness of a mailar plate versus velocity $H_{KR} = H_{KR}(V_0)$ (LLNL experiment, 1981) This curve "Propagation/Failure" was usually demonstrated for values {P, τ_{KR} }, were τ_{KR} is total time for the shock wave to travel the thickness of the plate H_{KR} and return the rarefaction wave to the "explosive/plate" boundary.

The calculations was executed with "quasisteady profile" for a developing detonation wave by variation in time of the reacted fraction F(t) at the maximum burning Lagrangian point after the wave front of

the detonation with the equation of conservation as usually (that is, in other words, at the "algebraic approximation level"). Two approximation were also used: "The noncompression plate" and "The approximation of the break disintegration". A good agreement was reached for both the case with the LLNL experiment data (1981).

The $P^*\tau_{KR} \approx$ const criterion was also considered. The new criterion predicts a more correct and more general interpretation for that:

$$1/\tau_{KR}(P) = ... + \alpha^*P^3 + \beta^*P^2 + \gamma^*P + \delta \qquad (6)$$

In view of the "Juge mobility point" conception the algebraical method for calculation of parameters characterizing the transition to the stationary mode of detonation is shown. Run distances to detonation and excess transit times were calculated successfully in the limit of the "thick plate" with LLNL reaction rates (1980 and 1995).

2D METHOD FOR NUMERICAL SIMULATION OF HE COMBUSTION AND DETONATION

O.A.Dibirov, S.V.Tsykin, Yu.V.Yanilkin

Russian Federal Nuclear Center, Arzamas-16, Russia

The presentation discusses a 2D method for simulation of high explosive (HE) combustion and combustion-detonation transition. The method is based on two-phase two-velocity representation of HE and HE combustion products (CP) and can be used for solid HE of various porosity degree. The method is implemented within the EGAK program system in the Lagrangian-Eulerian coordinates. The method of concentrations is used for computing both HE and CP component boundary motion across an arbitrarily moving computational grid.

Results of 1D test problem computations in comparison with exact solutions as well as those of 2D computations in comparison with experimental data are presented. The agreement is satisfactory.

COMPUTATIONAL STUDY OF PETN COMBUSTION TRANSITION TO DETONATION IN THE CONTEXT OF SEPARATED COMBUSTION FRONT MODEL

S.M. Bakhrakh, B.N. Krasnov, S.V. Tsykin, S.A. Shaverdov

Russian Federal Nuclear Center-VNIIEF, Arzamas-16, Russia

The combustion-to-detonation transition experiment for low porosity pressed peth is described theoretically and computationally. The

technique of numerical computations is discussed. The computed data and their comparison with the experimental results are used as a basis for the two-stage process evolution scheme providing for the possibility of transition to detonation with retaining the linear dependence of combustion rate on pressure inherent in most HE. A number of conclusions are made regarding each stage. The qualitative agreement of the computed and experimental data is obtained.

NUMERICAL MODELING OF EFFECT OF ALUMINUM PARTICLES ON DETONATION PERFORMANCE OF MODEL HIGH EXPLOSIVES BASED ON EQUILIBRIUM CHEMISTRY APPROACH

B.A.Khasainov[1], B.S.Ermolaev[1], A.A. Borisov[1], G.Baudin[2], H.-N. Presles[3]

Institute of Chemical Physics, Moscow, Russia, [2]Centre d'Etudes de Gramat - DGA, Gramat, France,[3]LCD, CNRS, Futuroscope, France

A model of aluminum oxidation in detonation products of condensed explosives is developed assuming diffusion (or mixing) controlled consumption of aluminum and "equilibrium chemistry" in reaction products in course of aluminum oxidation. Thus, state parameters and composition of detonation products along the particle path behind the shock wave are calculated assuming that they are in thermodynamic equilibrium. Particularly, we coupled directly 1-D gasdynamic code with a "black box" caloric equation of state which allows one to calculate pressure, temperature and composition of the mixture at given energy and volume of the mixture. This thermodynamic equilibrium subroutine is based on the program developed by Imkhovik N.A.[1].

We used our 1-D gasdynamic code to analyze performance and structure of steady detonation waves in HMX/Al mixtures at a given rate of decomposition of HMX and at different aluminum particle size and concentration. Apart from that, we used the code to simulate pyrometric studies and metal plate acceleration tests for HMX/Al compositions.

Detonation performance predicted by the code in extreme cases of fine and coarse particles reasonably agrees with thermodynamic equilibrium calculations for reactive or inert aluminum particles respectively. However, for the smallest aluminum particles the present version of the thermocode becomes not sufficiently reliable as aluminum

concentrations approaches 25% level, though in all other cases calculated results reasonably agree with thermodynamic predictions performed for extreme case of reacting aluminum and similar inert particles and provide valuable information on detonation product composition in and behind detonation waves. Apart from that, this "equilibrium chemistry" approach automatically provides correct energetics of the considered explosives. However, it is worth to rearrange the thermocode (i) by increasing its reliability at high aluminum content and respectively high temperatures exceeding 6000 K and (ii) by making it fully consistent with gasdynamic codes, i.e. the thermocode must be capable of finding directly pressure P and temperature T at given specific volume V and energy E of the detonation products without additional iterations. Such modification will allow one to reduce significantly computation time by avoiding excess iteration procedures of the kind used in this work and to couple the thermodynamic equation of state with 2-D gasdynamic codes.

Numerical gasdynamic simulations based on direct use of thermodynamic equation of state show that the smaller the particle size, the higher the temperature of HMX/Al detonation products. However, measurements of brightness temperatures demonstrate an opposite trend [2]. This qualitative difference between experimental detonation temperatures and thermodynamic calculations calls for either careful analysis of input data and equations of states used by the thermocode or reconsideration of the procedure used to extract detonation temperature of two-phase metal-containing mixtures by measuring brightness temperatures.

Simulations of metal plate acceleration tests show that addition of aluminum particles could provide about 3.5% gain in plate velocity in comparison with pure HMX if however particles are sufficiently small so that their characteristic burning time is significantly smaller than the particle dwell time in the considered experimental device. Hence, for any given firing assembly there is some threshold size of Al particles below which burning of aluminum enhances plate projection ability. Numerical results predict that there is an optimum concentration of aluminum ($\approx$15 wt. %) providing the largest plate acceleration effect.

The developed model of aluminum particle behavior in and behind detonation waves demonstrates as a whole high predictive ability. Apart from that, it can be applied to a number of different compositions and situations, especially being coupled with 2D gasdynamic code.

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OXIDATION OF ALUMINIUM PARTICLES IN THE PRODUCTS OF CONDENSED EXPLOSIVES DETONATION

N.A.Imkhovik, V.S.Soloviev

Moscow State Technical University, Moscow

In this work we investigated thermodynamical and macrokinetics properties of dispersed aluminium oxidizing under high dynamic pressures and temperatures, that take place in detonation of high mixed explosives. The analize is carried out on basis of combined usage of equilibrium chemical thermodynamics methods and hydrodinamics of reacting mediums approach. In terms of thermodynamics it was developed the allpurpose program system for numeric simulation of detonation parameters, detonation products (DP) composition and properties of various explosive mixtures. The perculiarities of aluminium behaviour in detonation of heterogeneous explosive systems with different characteristics: high density explosives, pourous and low density compositions,gaseous and airodusts. On basis of numerical and experimental data comparison it was shown, that the state of dispersed aluminium about Chapman-Jouget point and its affection degree on explosive detonation parameters is rather differ for various charge densities (high, porous, low) and oxidizing balanse (pozitive,negotive). Thermodynamic conditions of intermediate aluminium oxidizing products formation and high condensed oxid Al_2O_3 appearance were investigated. It was established a logic connection between reaction heat effect, products composition and properties and also with the effective external work. We also carried out analize of Hugoniots and rarefaction isentropes of equilibrium of partially "frozen" products composition sitation at the P-V plane. We realized that the positive oxidising

effect of aluminium, i.e., Q_{PV} grouth (instead of Q_{PT}) for the negotively ballansed explosives takes plase under rarefaction up to P<10 GPa. This explains impossibility of the rate and detonation pressure raise for high explosives by aluminium additions. The tendency of heat expandature increase with pressure decrease was noted eirlier (papers by Cook M., Belyaev A.F.), but was explained with specificy of chemical oxidizing mechanism (gaseous products appearance about Chapman-Jouget point - Al_2O, AlO).

Those thermodynamical properties of dispersed metal combustion under high pressures were used in numeric simulation of shocks and detonations propagation in reacting mediums with double-stage energy expansion, and also of plates and casings problem with mixed explosives. We investigated the influence of the time-scale factors and products gaseousdynamic flow on trasformation of the heat release of aluminium combustion into effective external word. On basis of that investigations, it was developed the allpurpose numeric-experimental method of aluminium oxidizing macrokinetics, determined by its affection on the medium's flow. The analize of experimental data was held and approximations were proposed for aluminium powders oxidising of various dispersity. The problem of oxidizing kinetics model creation for aluminium and other dispersed metals under high pressures is discussed.

РЕЛАКСАЦИОННАЯ МОДЕЛЬ ДЕТОНАЦИИ СМЕСЕЙ ВЗРЫВЧАТОГО ВЕЩЕСТВА С ИНЕРТНОЙ ДОБАВКОЙ *

Л.В.Альтшулер, В.С.Жученко[1], И.С.Меньшов[2]

Научно-исследовательский центр теплофизики импульсных воздействий, [1]Научно-исследовательский машиностроительный институт, [2]Институт прикладной математики, Москва, Россия

Предложена обобщенная математическая модель, позволяющая рассчитать параметры детонации взрывчатых веществ (ВВ), содержащих инертные добавки, с учетом температурной и скоростной релаксации в компонентах смеси. Схема расчета построена в рамках модели двухскоростной и двухтемпературной гетерогенной сплошной среды. В систему уравнений вводятся два релаксационных параметра, учитывающих затраты энергии и импульса на температурную и скоростную релаксацию. Фронт детонации считается бесконечно тонким, кинетика релаксационных процес-

сов в зоне энерговыделения не рассматривается, температура и скорость добавки на фронте волны задаются как входные параметры. Вычисления проводятся в два этапа. На первом этапе численно решается замкнутая система из трех нелинейных алгебраических уравнений, описывающих детонационную адиабату, прямую Михельсона и условие касания Чепмена-Жуге. При заданных релаксационных параметрах уравнения содержат три неизвестные величины - давление, удельный объем и скорость детонации. Решение системы определяет состояния смеси на фронте детонационной волны. На втором этапе рассчитывается нестационарная задача о распространении детонационной волны в взрывчатом веществе с примесью мелких инертных частиц, увлекаемых вязким потоком продуктов взрыва. Результаты вычислений описывают пространственное течение за фронтом детонационной волны.

Предлагаемая обобщенная модель позволила объяснить парадоксальные результаты, наблюдавшиеся при исследовании детонации смесей бризантного ВВ с порошком вольфрама (Альтшулер Л.В., Рязанов В.Т., Сперанская М.П.//ПМТФ. 1972. N1. С.122). Увеличение концентрации вольфрамовой добавки, вопреки расчетам по принятой аддитивной схеме, привело к резкому уменьшению давления детонации. В то же время измеренные скорости детонации оказались несколько выше расчетных значений. Вычисления показали, что в смесях ВВ с частицами из тяжелого металла скоростная релаксация играет доминирующую роль. Сопоставление расчетов с экспериментом показало, что степень завершенности скоростной релаксации на фронте волны увеличивается с ростом концентрации добавки α. При α=20% скорость вольфрамовых частиц примерно вдвое меньше скорости продуктов взрыва, последующий разгон частиц осуществляется за детонационным фронтом. При α=60% на фронте достигается почти полное скоростное равновесие. Расчетные профили детонационных волн выявили структуру, характерную для самоподдерживающегося режима недосжатой детонации с узкой зоной релаксации, в которой происходит интенсивное выравнивание скоростей продуктов взрыва и частиц вольфрама, а давление падает до некоторого равновесного значения, и последующей расширяющейся со временем областью с постоянными параметрами течения (плато). Давления в плато, рассчитанные для смесей с разным содержанием вольфрама (α=20, 40 и 60%), удовлетворительно совпали с экспериментальными данными.

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- *Relaxation Model of Detonation for Mixtures of Explosives with Inert Additive*, L.V.Al'tshuler, V.S.Zhuchenko[1], I.S.Menshov[2] (High Energy Density Research Center, Moscow; [1] Institute of Machine-Building, Moscow; [2] Institute of Applied Mathematics, Moscow)

МЕХАНИЗМ ДЕТОНАЦИИ ФЛЕГМАТИЗИРОВАННЫХ ВЗРЫВЧАТЫХ ВЕЩЕСТВ

Л.В.Альтшулер, В.С.Жученко[1], Н.А.Имховик[2], И.С.Меньшов[3]

Научно-исследовательский центр теплофизики импульсных воздействий, [1]Научно-исследовательский машиностроительный институт, [2]Московский государственный технический университет, [3]Институт прикладной математики, Москва

Исследования структуры детонационных волн в флегматизированных ВВ (тэне и гексогене, содержащих 5-10% парафиновой добавки) четко выявили характерные признаки самоподдерживающейся недосжатой детонации: увеличение скорости и снижение давления по сравнению с нормальным режимом Чепмена-Жуге, а также возникновение на профилях давления горизонтальных участков, растягивающихся по мере движения детонации по заряду (Альтшулер Л.В., Ашаев В.К., Балалаев В.В. и др.//ФГВ. 1983. N4. С.153). Наблюдаемый режим был качественно интерпретирован с классических позиций: предполагалось, что недосжатая детонация возникает из-за немонотонного тепловыделения, вызванного затянутой эндотермической реакцией разложения парафина. Численный анализ, проведенный в данной работе, показал неточность такой трактовки.

При детонации флегматизированных ВВ взрывчатое превращение сопровождается различными релаксационными процессами, в том числе разложением парафиновой добавки. Продукты разложения парафина вступают в химическое взаимодействие с продуктами взрыва, при этом протекают как эндотермические, так и экзотермические реакции. Конечное состояние продуктов взрыва определяется не только суммарным тепловым эффектом, но и изменившимся химическим и фазовым составом смеси.

Проведенные термодинамические расчеты определили параметры состояния на промежуточной адиабате (смесь продуктов взрыва с ударносжатым исходным парафином) и на конечной адиабате (смесь нового состава). Оказалось, что различия в тепловых эффектах промежуточного и конечного состава малы, а немонотонное смещение детонационных адиабат на плоскости давление - удельный объем в процессе химического превращения обусловлено не теплопотерями, как ранее предполагалось, а изменением ударной сжимаемости и термодинамических свойств конечных продуктов взрыва.

В реальных зарядах флегматизатор распределен неравномерно, как в виде тонких микронных пленок, покрывающих поверхность зерен ВВ, так и в виде относительно крупных включений, расположенных между зернами. Вследствие этого часть флегматизирующей примеси может разлагаться очень быстро, внутри химической зоны превращения ВВ, а часть - замедленно, в волне расширения. Количественное описание поведения парафина в детонационной волне вряд ли возможно. В проведенных газодинамических расчетах кинетика разложения задавалась экспоненциальным законом, при этом варьировались три параметра: время релаксации, доля парафина, разложившегося в зоне химического превращения ВВ, и общая доля парафина, разложившегося в зоне релаксации.

Газодинамическое моделирование с использованием результатов термодинамического анализа выявило типичную для недосжатой детонации картину течения с быстрой зоной релаксации и последующим автомодельным плато, переходящим в центрированную волну разрежения. Вычисленные параметры детонации удовлетворительно согласуются с экспериментальными данными.

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- *Mechanism of Detonation of Flegmatizated Explosives.* L.V.Al'tshuler, V.S.Zhuchenko[1], N.A.Imkhovik[2], I.S.Menshov[3] (High Energy Density Research Center, Moscow; [1]Institute of Machine-Building, Moscow; [2]Moscow State Technical University, Moscow; [3] Institute of Applied Mathematics, Moscow)

МОДЕЛИРОВАНИЕ НАГРУЖАЮЩЕЙ И МЕТАТЕЛЬНОЙ СПОСОБНОСТИ НИЗКОПЛОТНЫХ ВЗРЫВЧАТЫХ СОСТАВОВ *

С.Г. Андреев, М.М. Бойко, Н.А. Имховик, И.П. Мачнева, В.С.Соловьев

Московский государственный технический университет, Москва

В настоящее время наряду с высокобризантными взрывчатыми составами все большее применение находят низкоимпульсные и, в частности, низкоплотные взрывчатые составы (НПВС), обладающие комплексом свойств, позволющим реализовывать необходимое соотношение нагружающей и метательной способности ВВ. В первом приближении это соотношение получено аналитически с использованием:

- в качестве характеристики метательной способности - скорости метания несжимаемой пластины продуктами детонации (ПД), распространяющейся в режиме Чепмена-Жуге (Ч-Ж) в направлении, противоположном направлению ускорения пластины (уходящая детонационная волна (ДВ)),
- в качестве характеристики нагружающей способности - значения максимума давления, развиваемого на границе контакта ПД уходящей ДВ с веществом (материалом пластины) заданной сжимаемости.

Одномерное плоскосимметричное расширение ПД описывалось с использованием уравнения изоэнтропы $\mathbf{P = A}\rho^{\mathbf{k}}$, в которой зависимость параметров **A** и **k** от начальной плотности НПВС определялась в соответствии с подходом Юкавы и Миллера. При этом ВВ, плотность которого меньше кристаллической, представлялось смесью двух фаз - первой с плотностью монокристалла и второй - гипотетической с плотностью, равной нулю. Эксперименты показали приемлемость такого подхода лишь для некоторых ВВ и их смесей с небольшим количеством малоплотных наполнителей (например для гексогена (Г) и его смеси с мипорой (ГМ)).

В настоящей работе использован термодинамический подход, позволивший проанализировать соотношение нагружающей и метательной способности для более широкого круга НПВС на основе гексогена (включая смеси с фенолформаль-дегидными микросферами (ФМС) и бакелитом (Б), алюминием (Al) и ВВ - окислителями: аммиачной селитрой (АС), перхлоратами аммония (ПХА) и калия (ПХК) и НПВС на основе сплава ТГ с пенополистиролом

и Al (ТГПС и ТГАПС) и сопоставить их характеристики с данными для хорошо изученной смеси ГМ.

Так как термодинамическое равновесие ПД в плоскости Ч-Ж смесевых ВВ может не достигаться, в общем случае использовались три варианта расчета, соответствующие идеальному (вариант I) и неидеальным (варианты II, III) режимам детонации. Параметры неидеальных режимов определялись при заданном частичном тепловом и химическом неравновесии ПД. При расчете по варианту II в плоскости Ч-Ж неравновесной (нереагирующей) считалась лишь добавка Al; по варианту III учитывалось разложение только наиболее детонационноспособного компонента - гексогена, а все другие (Al, ВВ-окислители, ТНТ, наполнители) считались нереагирующими до плоскости Ч-Ж и сжимаемыми аддитивно с ПД гексогена.

В качестве критериев оценки баллистических характеристик НПВС, отражающих специфику их применения и позволяющих проводить аналитические вычисления скорости метания для некоторых геометрических схем, приняты: характеристическая скорость ПД при изэнтропическом расширении (W*) и выделившаяся вдоль изэнтропы объемная внутренняя энергия (E*). При одинаковой плотности зарядов наиболее высокие значения характеристик W* и E* реализуются для состава ГМ. Близки к нему состав ТГПС и его смесь с Al при оптимальном (~10%) содержании добавки и ее полном окислении. Одновременное введение 20% Al и 15 % ВВ-окислителей (АС, ПХА), несмотря на существенное увеличение теплоты взрывчатого превращения Q, не дает заметного повышения W* и E* из-за снижения параметров детонации, что в свою очередь является следствием снижения количества молей газообразных ПД в плоскости Ч-Ж (для состава Г/ПХК/Al/ФМС/Б, несмотря на максимальное Q, значения W* и E* минимальны).

Вместе с тем, если анализировать метательную способность НПВС с учетом ограничений по давлению нагружения уходящей ДВ, а также дополнительных ограничений на объем заряда НПВС и базы разгона метаемых элементов, то ряд по метательной способности существенно изменится. При этом наиболее эффективными становятся составы с Al и окислителями (АС, ПХА). Сравнение результатов расчета с экспериментальными данными для различных условий применения НПВС, показало качественное соответствие между расчетными и эксперимен-

тальными опорными рядами НПВС по их нагружающей и метательной способности.

* *Modeling of Throwing and Loading Ability of Low Density Explosives.*
S.G.Andreev, M.M.Boiko, N.A.Imkhovik, I.P.Machneva, V.S.Soloviev
(Moscow State Technical University, Moscow)

ФОРМИРОВАНИЕ ТЕПЛОВОГО СЛОЯ НА ОСЕСИММЕТРИЧНОМ КОНТАКТЕ СКОЛЬЖЕНИЯ В РЕЖИМАХ ФРИКЦИОННОГО ТЕПЛООБРАЗОВАНИЯ С ИЗНОСОМ

А.В.Аттетков, И.К. Волков

Московский государственный технический университет, Россия

В проблеме ударно-волновой чувствительности особое место занимают исследования механизмов тепловой диссипации в гетерогенных энергетических материалах (ЭМ) при динамических воздействиях. Гетерогенность структуры ЭМ является причиной возникновения неоднородных полей напряжений, деформаций и температур, что связано с проявлением эффектов мезомасштабных движений и приводит к образованию в ударно-сжатом ЭМ так называемых горячих точек - локализованных областей динамических перегревов.

Несмотря на интенсивные исследования по рассматриваемой проблеме открытым остается вопрос о механизмах локализации энергии ударного сжатия в гетерогенных ЭМ, содержащих высокоплотные дисперсные включения. Отличительная особенность динамического поведения ЭМ данного класса - возможность проявления эффектов проникающих перемещений. Инерционным расслоением фаз гетерогенных ЭМ с дисперсными включениями, неизбежно сопровождаемым взаимодействием процессов фрикционного теплообразования и изнашивания на скользящем контакте, можно объяснить их повышенную ударно-волновую чувствительность по сравнению с гомогенными ЭМ.

В докладе обобщаются результаты исследований по проблеме формирования теплового слоя на осесимметричном контакте скольжения при трении с износом. Математическая модель исследуемого процесса, учитывающая температурную зависимость силы трения и взаимодействие процессов фрикционного теплообразования и изнашивание на нестационарном скользящем контакте, имеет вид:

$$\frac{\partial\theta}{\partial\tau}=\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial\theta}{\partial\rho}\right),\ (\rho>R(\tau),\tau>0)$$

$$\theta(\rho,0)=0;$$

$$-\rho\frac{\partial\theta(\rho,\tau)}{\partial\rho}\Big|_{\rho=R(\tau)}=\varphi(\tau)\left\{1-\theta(\rho,\tau)\Big|_{\rho=R(\tau)}\right\}.$$

Реализуемый режим фрикционного теплообразования однозначно устанавливается конкретизацией вида функции $\varphi(\tau)$, а закон изнашивания - заданием функции $R(\tau)$. В частности, на установившейся стадии процесса изнашивания $R(\tau)=C\tau$, $C=\text{const}$.

Подробно изучен режим фрикционного теплообразования при отсутствии износа на скользящем контакте ($R(\tau)\equiv R=\text{const}$). Получено обобщение интегрального преобразования Вебера и предложен аналитический метод решения исходной задачи, основанный на расщеплении ядра обобщенного интегрального преобразования Вебера по пространственной переменной ρ. Аналитически замкнутая форма представления решения, определяющего температурное поле в области $\rho\in[R,\infty)$ при произвольном законе $\varphi(\tau)$ движения осесимметричного источника. имеет вид:

$$\theta(\rho,\tau)=-\frac{2}{\pi}\int_0^{\infty}\int_0^{\tau}\frac{K(\rho,\lambda,t)}{\alpha^2+\beta^2}\varphi(t)\exp\left\{-\lambda^2(\tau-t)\right\}\lambda dt d\lambda;$$

$$K(\rho,\lambda,t)\equiv(1/2)\left[(\alpha+i\beta)H_0^{(1)}(\lambda\rho)+(\alpha-i\beta)H_0^{(2)}(\lambda\rho)\ \right],$$

$$\alpha\equiv\varphi(t)Y_0(\lambda R)+\lambda Y_1(\lambda R),\beta\equiv\varphi(t)J_0(\lambda R)+\lambda J_1(\lambda R).$$

($J_\nu(\bullet)$ и $Y_\nu(\bullet)$; $\nu=0,1$ - функции Бесселя 1-го и 2-го рода соответственно, $H_0(\bullet)$ - функция Ганкеля).

Исследовано влияние эффектов изнашивания ($R(\tau)=C\tau$) на процесс формирования теплового слоя на осесимметричном контакте скольжения в различных режимах фрикционного теплообразования. Показано, что изнашивание контактирующих поверхностей в процессе фрикционного нагрева приводит к снижению величины предельно допустимого разогрева. Теоретически обосновано, что для высокоплавящихся ЭМ (октоген, гексоген, ТЭН) температура плавления является верхней границей максимально достижимого разогрева на скользящем контакте. В тоже время,

для легкоплавких ЭМ (тротил) возможность реализации режимов фрикционного теплообразования с образованием жидких прослоек в тонких поверхностных слоях контактирующих материалов и достижения в них значительных перегревов, сохраняется.

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THERMOMECHANICAL MODEL OF SOLID PHASE DETONATION OF LEAD AZIDE

Knyazeva A.G., Dyukarev E.A.

Institute of Strength Physics and Materials Science, Siberian Branch of RAS, Tomsk, Russia

The heavy metal azides are the classical object of investigations in physics of combustion and explosion of condensed systems. They are able as to the slow thermal decomposition and so to the detonation in classical since. It is known, that the reaction product does not cross into gas phase until crystal decomposes, and stays in solid matrix in absorbed or dissolved state due to crystal fracture. The special experimental study in this region allows to assert that appearing during chemical reaction temperature gradient and difference in molecular volume of reagent and product lead to appearance of mechanical stresses, the following relaxation of which according to various channel favours the acceleration of reaction of solid phase decomposition. The separation of reaction into solid phase and gas phase stages and the basic role of mechanical processes for reaction kinetics are typical for any regime.

In this paper, the explanation of the existence of two different regimes of decomposition (subsonic and supersonic) in solid phase for heavy metal azides is suggested on the base of thermomechanical model of solid phase combustion, where the thermal expansion and change of substance volume during chemical conversion are taken into consideration. The analysis of numerical results has shown that "deformation" mechanism of energy transfer is basic for solid phase detonation wave, and thermal conductivity gives only spreading of this wave front, that has observed in classical detonation. The subsonic regime of reaction propagation may be called as thermal, since energy transfer happens here by thermal conductivity. The heat release due to chemical reaction and due to thermal expansion tells on the energy balance of system in various ways for different regimes. The qualitative

investigation has allowed to assert that basic change of density goes in the region, where the reaction is completed, if wave is subsonic, and density changes into reaction zone, if wave is supersonic. The calculations of temperature and rate of reaction wave are carried out for other explosives, for which the role of mechanical processes is suggested as important on the base of experimental dates. That allows to find from inverse problem solution the new parameter (nondimensional coefficient of concentration expansion), included in thermomechanical model of combustion. The numerical dates satisfy the experimental investigations.

The fracture in reaction zone (by kinetic law) and the corresponding heat effect are taken into consideration in improved variant of mathematical model. It is received that chemical reaction wave runs along the complete destructing specimen as for slow, so for quick regime. It was detected that product output is approximately 35 %, that aggries also with experimental dates.

SESSION "Advanced Explosives: Theory and Practice"

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THE NON-EXPLOSIVE CHEMICAL-ACTIVE ADDITIVES INFLUENCE ON EXPLOSIVE DECOMPOSITION UNDER LOW VELOCITY MECHANICAL AND SHOCK WAVE EFFECTS

S.G.Andreev

Moscow State Technical University, Moscow

One of tendencies to improve the correlation efficiency and explosive hazard of energetic materials (EM) is the usage of moderate quantity additives, that influence on the final composition of decomposition products (DP) and on the heat of reaction is inessential. Under these conditions the EM explosive performances changing is worked for achieving largely on account of additive property to inhibit chemically the processes. These properties supplement physical effect. These additives can be named as non-explosive non-energetic chemical-active additives (NCAA). The NCAA, considered in this study, are introduced into charge as films, powders on external free surfaces of EM particles.

The practical part of the problem of EM desensibilization makes necessary the investigation of NCAA influence on the explosive process development under different dynamic mechanical effects (which are most probable at EM application). The EM performances of sensibility to mechanical low-velocity impact, dynamics of energy liberation in weak shock waves (SW) and detonation capability largely define the EM danger under these effects. The information about NCAA influence on those performances is useful and for the theory of EM.

The studies of numerous researchers, (according to the author) above all: Andreev K.K. and Glazkova A.P., Camlet M., Karpuhin I.A., Walker F.E,, Wasley R.J., Kondrikov B.N., Svetlov B.S., published in 50th-70th, established the basis of qualitative theory of EM sensorialization by NCAA. The publications devoted to practical application were apparently started in 70th-80th. It is necessary to note the publications of Walker F.E., Wasley R.J., Schur J.M. with co-

authors. At the same time the publications, devoted not immediately to NCAA, but expanded considerably the conception on efficiency of NCAA influence at explosive EM performances, had appeared. In the study the various information, directly or indirectly devoted to NCAA, is discussed. It is connected with that the NCAA efficiency is appeared as a result of juxtaposition of influence of physical and chemical properties of charge compounds and it's structure on explosive EM performances.

The influence of last three factors is discussed within the framework of existed apprehensions (or their generalizations) about:

- decomposition velocity field heterogeneities in gas-dynamic macrohomogeneous reacting material;
- initiation mechanism of initial act of molecule decomposition;
- the role of derivative reactions of EM molecule decomposition;
- itemized (expanded) conception of hot spots (HS) and decomposition hearts (DH);
- the influence of HS structure on formation DH;
- homogeneous thermal EM decomposition (including reactions at CO2-laser radiation of molecule bunch and EM thin film) and deformation-catalytic EM decomposition in HS;
- the influence of micro- and macro-structural heterogeneities of charge on HS and DH formation;
- the critical conditions of explosive transformations propagation.

With a view to simplify the problems of peculiarities extraction of NCAA chemical properties influence on sensibility performances and EM detonation capability, the mixture of one of the most explored material - RDX with various additives, including NO2 radical traps - is considered. On the basis of generalizations of author's experiment results, experimental and theoretical studies of other researchers the following conclusions and hypothesises were made.

HS, formed under dynamic mechanical effects, should be generally considered as the areas of thermal and deformation-catalytic reaction acceleration before explosive appearance. Initial molecule decomposition mechanisms of the same material, proved in HS, can be various, described by theories, including simplest thermal, molecular-dynamic, quantum-mechanical. The reaction evolution up to final DP in HS largely depends upon phase state of reagents in HS and HS structure. The NCAA introduction into EM charge imminently results in changing it's initial and gained structure. Thus NCAA influence on sensibility performances and detonation capability not only through

influence on chemical mechanisms but through traditional factors analyzed in sensorialization problems.

Direct additives chemical influence on EM explosive performances are connected with catalytic direction of transfer process of EM and NCAA into final DP and capability of NCAA and its decomposition product to connect active intermediate DP (radicals). For nitroamins and numerous other EM of CH(NO2) group such initial products are NO2 radicals. For the first stage of EM decomposition NCAA can influence, apparently mediate, by changing molecular interaction at the areas of matrix distortions and inter-phases.

The additive "non-chemical influence" on charge decomposition are generally connected with structural (micro-structural) changing physical and mechanical, realign, thermal and physical, thermodynamic and gas-dynamic factors. These factors influence on distinctive features of HS formation and DH development.

In general NCAA can differently influence on reaction, defining the HS ignition (DH concentration), and reaction, defining the DH growing (to change burning rate around DH). NCAA selectively affect on reactions, defining EM sensibility to mechanical impact, weak SW, detonation capability. The distinctive features of this appearance were noticed. Although there are grounds to assume the NCAA action similarity on EM decomposition under weak SW and EM detonation capability.

The charges, based on RDX with similar (before pressing) initial disperse and close porosity after pressing at availability in desensitizing additive, spread on the surface of initial EM crystals, trap properties, are noticed the minimal detonation capability. This effect is considered within the framework of discussion about charge structure influence on they detonation capability and decomposition velocity in strong SW.

The EM desensibilization efficiency of NCAA, fixed on the grain surface, is largely limited by the fact, that DH can be formed not only on the crystal surface but on inter-grain defects, unapproachable for NCAA at DH forming stage.

EFFECT OF GLASS MICROBALLOONS ON SHOCK SENSITIVITYOF MODEL PBX

B.A. Khasainov, M.K. Sukoyan, B.S. Ermolaev, A.A. Sulimov, A.A. Borisov, Yu.M. Mikhaylov, H.-N. Presles*

*Institute of Chemical Physics, Moscow, Russia; * LCD, CNRS, Futuroscope, France*

Shock-to-detonation transition (SDT) in plastic bonded explosive sensitized by thin-walled glass microballoons (GMBs) is investigated using modified wedge test. The special technique is developed to prepare mixtures of practically nonporous matrix (comprising HMX and inert binder) with GMBs, that allows one to control and vary easily characteristics of microstructure of heterogeneous PBX in a well defined range. Porosity of tested PBX was varied from 1.8% to 10.8% and GMB specific surface area from 2.5 mm^{-1} and 18 mm^{-1}. GMBs of five different kind with diameter ranging from 20-45 μm to 100-125 μm were used. Four of five kinds of GMBs had practically the same wall thickness to diameter ratio, i.e., ≈1.5 μm/(45-63 μm), while the fifth one had nearly 3 times smaller relative GMB wall thickness, namely, ≈0.5 μm /(50-63 μm).

Effect of GMB concentration, size and wall thickness on run distance to detonation at different amplitudes of triangular shock wave (5-8 μs long) entering 40-mm diameter explosive sample was studied. Run distance to detonation, L, decreased from ≈10 mm both for nonporous and porous samples at impact pressure, P, of ≈3.5 GPa to ≈4.5 mm for the nonporous matrix and to ≈3 mm for explosive sensitized by thicker-walled GMBs at impact pressure ≈8 GPa. At low pressures sensitizing effect of GMBs is not observed. For the matrix experimental data are described as $L=34.9/P^{0.95\pm0.09}$ with $[L]$=mm and $[P]$=GPa ($R^2=0.94$).

Thus, GMB-sensitization effect in the tested multi-component heterogeneous explosive is weaker than could be expected based on available data for heterogeneous individual explosives which demonstrate existence of linear correlations between different shock sensitivity characteristics and specific surface area of heterogeneous explosives [see review by Khasainov B.A., Ermolaev B.S., Presles H.-N., Vidal P. (1997) *On the effect of grain size on shock sensitivity of heterogeneous high explosives.* Shock Waves 7:89-105].

This trend can be attributed to a layer of inert binder (polybutadiene) separating HMX and GMBs. Mean thickness of this binder film amounts to a few micrometers that can provide efficient thermal protection of HMX grains from potential hot spots resulting from GMB collapse. This conclusion is supported by comparison of experimental data for thinner- and thicker-walled GMBs. Indeed, at the same parameters of plane wave generator and at the same porosity of studied explosive material the thinner-walled GMBs provide significantly smaller run distance to detonation than do thicker-walled GMBs. The protective effect of binder film becomes less important as impact pressure grows.

At relatively high impact pressures the run distance to detonation, $L(P^*=Const)$, linearly increases as reciprocal GMB specific surface area is increased at constant thickness of GMB walls. The smaller thickness of GMB walls, the higher the slope of $L(1/A_s)$ dependence.

The model of hot spot initiation and growth in heterogeneous PBX sensitized by glass microballoons is proposed and coupled with "macroscopic" one-dimensional gasdynamic model of shock-to-detonation transition. Results of calculations reasonably agree with experimental trends, particularly, on the effect of wall thickness and specific surface area of GMBs on dependence of run distance to detonation on impact pressure P. The model predicts also shock sensitivity reversal effect for the dependence of $L(P^*)$ on $1/A_s$ when porosity of explosive material approaches 30-40%. The higher GMB wall thickness and/or thickness of binder film separating HMX crystals from GMBs, the lower the efficiency of GMB voids in local ignition of HMX, that is both binder and glass layers can provide efficient thermal protection of HMX crystals, especially, at low impact pressures. Nevertheless, there are still important difficulties in describing hot spot growth stage in shocked heterogeneous explosives.

Acknowledgement

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MODELLING OF DETONATION PARAMETERS OF FLUORINE CONTAINING HE AND THIER CONPOUNDS WITH ALUMINUM

N.A.Imkhovik

Moscow State Technical University, Moscow, Russia

The production of high energetic HE-oxidizers containing active fluorine and active oxidizer in molecular is one of the perspectives of the further development of explosive compounds and rising of rocket propellants power. As an example of such materials development in the paper [1] a number of unique chemical compositions is presented including fluorine containing oxidizer ($C_4 H_4 N_8 O_{10} F_4$) of high-density possessing record blasting properties in a compound with aluminum at present.

Detonation parameters, equilibrium compound and detonation products (DP) properties have been analyzed on the base of thermodynamic calculations over a wide range of liquid and solid fluorine containing HE and their mixtures with fine aluminum powder in the paper. Some tentative containing fluorine materials with C - F, N - F, O - F linkages and based on them compounds of high energy concentration in unit of volume have been considered.

The comparison of thermodynamic calculation results with available test data for 10 fluorine containing HE showed, that the average value of deviation module (when calculating by BKW) is about 3% in detonation velocity and 10% in DP at Chapman-Jouget point, that is worse generally, than for conventional and well studied CHNO-HE (relative error does not exceed 2% in detonation velocity and 5% in pressure for more than 50 CHNO-HE).

The character of changes of on the base of CNF-, CHNF-, CHNO- and CHNOF-HE of the current DP composition, specific reaction heat Q_{pT} and ratio of specific heats k at isentropic expansion from Chapman-Jouget condition has been studied. The change of composition and properties of fluorine containing HE DP is connected especially with content decrease of CF_4 dominating at high pressures and HF content increase. At low pressures multi-atoms molecules CF_4 in equilibrium composition of DP are practically absent (hereupon they are not found experimentally in calorimetric tests [2]), and HF content is approaching to the maximally probable value. The last one results in average molecular mass decrease of gaseous DP and improvement of their performances as an working medium. In default of

hydrogen in HE molecular, as for example in PFB mixture, base components of DP are N_2, CF_4 и $C_{cond.}$ and their content at isentropic expansion is not changing practically. This peculiarity (DP composition permanency) is preserved and for stoichiometric (in AlF_3) mixture with aluminum. On account of high temperatures aluminum fluorides are present in DP as gases. However the gaseous phase content and for PFB, and for its mixture with Al is very low (only from 12 to 13 moles per HE kilogram in comparison with form 30 to 38 moles for other fluorine containing HE). The consequence of that is comparatively low velocities and pressures of detonation of stoichiometric compounds, in spite of high heats of their explosive decomposition Q_{pT} [2].

In addition AlF_3 may be present not always in DP in a gaseous form. Calculations have indicated for Al mixtures with more energetic HE (including HE with $C_4 H_4 N_8 O_{10} F_4$), that the highest aluminum fluoride in Chapman-Jouget flat exists as a condensed phase. At DP isentropic expansion the pressure decreases intensively and at a certain stage $(AlF_3)_{cond.}$ passes into a gas. However, as DP expanse further, the temperature becomes lower than 1600 K and $(AlF_3)_{gas.}$ are completely condensed.

Although the question of Al reaction degree in Chapman-Jouget flat is open even for CHNO-HE [3], the DP expansion character at plates and shells blasting by HE charges have indicated the sufficiently rapid oxidizing of fine Al particles in detonation wave (during instants from several units to several tens of μs). In this case the realization of the most part of aluminized HE energy in effective forms of an explosion work takes place at large degrees of DP expansion (explosive action). The thermodynamic calculation of the total perfect working capacity of aluminized HE DP has been performed, and the evaluation of their potential blasting action at different (characteristic for cylinder-test) DP expansion degrees and various assumption of aluminum reaction degree has been presented.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПРОЦЕССА ВЗАИМОДЕЙСТВИЯ АЛЮМИНИЯ С ПОЛИТЕТРАФТОРЭТИЛЕНОМ В УСЛОВИЯХ УДАРНОГО НАГРУЖЕНИЯ

А.В.Стыров, В.В.Селиванов[1]

Нижнетагильский институт, Нижний Тагил, Урал; [1]Московский государственный технический университет, Москва

Представлены результаты экспериментального исследования процесса высокоскоростного взаимодействия бойков из ПТФЭ и комбинированных ударников, содержащих элементы из ПТФЭ, с преградами из алюминиевых сплавов различного типа. Изучалось влияние скорости соударения, массы, удлинения и формы головной части ударника из ПТФЭ, его начальной температуры, наличия и толщины металлической оболочки, присутствия в составе сборки порошкообразного алюминия и других факторов на параметры формирующейся в преграде каверны и сопутствующие процессу ее образования эффекты, связанные с химическим взаимодействием материала ударника и преграды.

Эксперименты проводились на баллистических установке, позволяющей метать ударники диаметром d_y = 13, 23 и 33 мм, длиной от 1 до 12 калибров со скоростями 300 ... 1500 м/с. В качестве преград использовались листы и плиты из алюминиевых сплавов АМц, АМг5, АМг6, Д16 и многослойные пакеты из названных материалов.

При стрельбе бойками из полиэтилена, эбонита, текстолита и фторопласта по алюминийсодержащей преграде (АМц) получены каверны, отличающиеся по своим параметрам (все эксперименты проводились в нормаль, кинетическая энергия ударников фиксировалась). Наибольшие параметры каверны по диаметру $d_к$, глубине $h_к$ и объему $V_к$ соответствовали бойкам из фторопласта. Кроме этого экспериментальные исследования показали, что при использовании ударников из ПТФЭ и скоростях соударения ПТФЭ и алюминиевой преграды 600 м/с и выше на поверхности каверны и вокруг нее образуется черный налет карбонированных продуктов. С целью определения их состава собранные из каверны с помощью препаровальной иглы частицы черного цвета подвергались рентгенофазному анализу, который показал, что исследуемые частицы состоят из металлического алюминия и фторида

алюминия AlF_3. Черный цвет этих частиц вызван наличием на них сажи.

Получены аппроксимирующие зависимости относительных параметров каверны (d_k / d_y; h_k / d_y; V_k / V_y) от скорости соударения для полубесконечных преград и рассмотрены особенности пробития сплошными и комбинированными ударниками конечных ($h_п \sim d_y$) и слоистых преград. Проведена скоростная фоторегистрация процесса соударения (показавшая наличие свечения продуктов реакции, более длительного чем при воздействии инертных ударников) и получены оценки избыточного давления во фронте воздушной ударной волны, генерируемой при ударе бойков из ПТФЭ (и ударников, содержащих ПТФЭ и алюминий) по алюминий содержащей преграде.

* *Experimental Studying the Process of Interaction of Aluminium with Polytetrafluoroethylene under Shock Compression,* A.V.Styrov, V.V.Selivanov[1] (Nizhny Tagil Institute at Ural State Technical University, Nizhny Tagil, Russia; [1] Moscow State Technical University, Moscow)

ON SHOCK-WAVE PROPERTIES OF CuO/B MIXTURE

E.A.Dobler, A.N.Gryadunov, A.V.Utkin*

*Institute of Structural Macrokinetics, Chernogolovka, *Institute of Chemical Physics, Chernogolovka, Russia*

In connection with recent interest in a possibility of producing detonation in systems which react without formation of gas-phase products ("gasless detonation"), special attention should be given to condensed systems which react with a considerable volume increase. In the present work the results of an investigation of the shock-wave properties of a CuO/B mix are presented. In the course of reaction in this mix the volume increases substantially (the volume increases by 28%, the thermal expansion effects not taken into consideration). The experiments were performed on mixtures with components of different particle sizes: 20 and 1.6 micron powders of CuO, 5 and 1.5 micron boron powders. The pressure profiles in the coarse -grained and fine-grained mixes of CuO/B and in a pure fine powder of CuO were obtained experimentally. The analysis of the received structures suggests that the speed of interaction in the system CuO-B behind the shock front during at least 2 mks is insufficient to affect the pressure profile and does not exceed 10^5 c^{-1}. To answer the question on a possible depth of transformation in the shock front itself, the experimentally received

parameters of the shock adiabates in the system under discussion were compared with the theoretical Hugoniots designed using the properties of the components. In order to estimate the thermodynamic parameters of CuO at pressures and internal energies of the experimental conditions, experiments on determination of the CuO shock adiabat were also performed. The experiments have shown that the equation of state for CuO in the range of pressures and energies characteristic of the experimental conditions can be expressed in the Mie-Gruneisen form: $P=K\cdot(R/r_0-1)+E\cdot\gamma\cdot r$, where P-pressure, K=150 GPa, r_0 - density of CuO at normal conditions, r - density, E - specific internal energy and $\gamma=1$ - Grunaisen coefficient. Calculations have shown, that the conversion depth of approximately 15% is needed to shift the theoretically evaluated coordinates of final states in centre of the region of experimental results (near points 4, 11 on the Fig.1).

The effect is most distinguished for fine-grained mix (misplaced points of 8-11) and only slight in case of coarse-grained mixtures (points 3,4). Nevertheless, the obtained results do not unequivocally support the occurrence of a chemical process in the shock front. It is possible for example that the effect is due to a change in the humidity of the samples which was not controlled by any appropriate procedure.

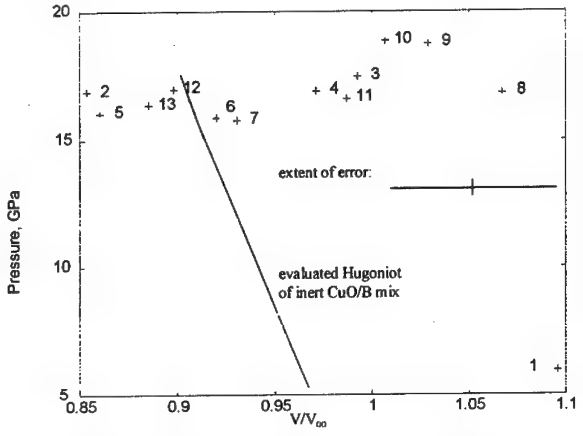

Fig.1. Experimental points and evaluated Hugoniot of inert CuO/B mixture.

Here: V-the specific volume after shock, V_{00}- the specific volume of zero porosity mixture at normal condition. Points 1-7 –coarse grained mix, 8-13 – fine grained mix.

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MODEL OF IMPACT DECOMPOSITION OF POLYTETRAFLUOROETHYLENE

V.A.Pyr'ev, V.V.Selyvanov

Moscow State Technical University, Moscow, Russia

Polytetrafluoroethylene (PTFE) — polymer with a beside of exclusive properties, that allows widely to use it in engineering. The large interest represents PTFE behaviour at high speed impact. Several tests have been performed with an impact velocity of 100-1000 m s^{-1} with cylindrical projectyle by a diameter of 30 mm from PTFE on aluminium barrier by thickness of 200 mm. After impact, accompanied by flare, is observed condensed carbon and AlF_3 in the vicinity of caverne. Formation of condensed carbon — this consequence of reactions in a gas phase is established, that at disintegration of a primary product of thermal destruction PTFE — tetrafluoroethylene (TFE). Temperature of thermal disintegration PTFE $T_{кр} \approx$ 700-1000 K /1, 2/ not achieved with shock-wave compression and plastic deformation of sample PTFE. It can be realized at local heating, at that it not occurs on the hot spot of microstructure of a sample during passage shock wave, about than results of experiments on loading PTFE powerful shock wave at in short duration /3/. Heating, depolymerisation and explosive reaction TFE rather as macroscopic shear deformation in PTFE due to penetration processs. He are realized at low pressure at stages of operation projectyle on a barrier in result of high-speed friction on surfaces of microshifts and microdestructions, and also at impact fragment of a material.

With the purpose of an estimation heating PTFE at high-speed friction a problem in statement similar /4/, formation plastic and liquid layers was decided. Characteristics of high-speed friction PTFE is revealed: formation a liquid layer does not come, in spite of the fact that the thermal condition of its formation comes of units μs. It is connected that because of large meaning of viscosity PTFE the second condition on border of layers — equality of strain of shift of plastic and liquid phases is not carried out. Account shows, that width subheating is higher than melting temperature of a layer is increased, its average temperature grows and at the moment of the order of tens μs of thermal decomposition temperature of PTFE becomes higher.

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CREATION AND INVESTIGATION OF ULTRATHIN CHARGES OF HE

D.A.Vlassov

Saint-Petersburg State Technological University, Saint-Petersburg, Russia

Peculiarities of detonation in ultrathin charges (30-60 mkm) are worth studying. The relation $d_{cr} = 2\ C\tau$ having beea drawn by Y.Khariton and used for estimation of critical diameters for charges shows only the fundamental appointment of these relations. In Saint-Petersburg State Technological Institute the problem of creation of charges with the thickness of 40-60 μm is under consideration.

The creation of charges with such thickness using mechanical or moulding methods is impossible. We have created the method of getting layers of explosive materials and any other organic substances of any desirable low thickness. The idea of this method deals with thermal vacuum - evaporation of explosive material using special device VUP-5 (vacuum universal post). There is no problem in powdering of tthe layer on any given solid basis (metal foil, polymeric film, and any other solid or elastic basis).

Using electron microscopic investigations it has been proved that evaporation of organic substances including explosive materials takes place according to the mechanism of fragmentation. This means the evaporation of tiny fragments of the crystal. The molecular evaporation is the second order problem. The level of packing for fragments in the powdered layer is rather great and is about 0,8-0,9 of the monocrystal density. The size of fragments in the layer differs from submicrones to 3-6 μm. The value of detonation velocity for explosive materials in the layer of 40-100 μm equals to 80-92 percents of ideal detonation velocity for the given explosive material.

The lowest value of critical thickness for the layer has been registrated for explosives in rows of furozane and furoxane.

We have also investigated some peculiarities of detonation in thin layer charges. Thin layer charges on solid and plastic basis made by thermo-vacuum evaporation can be used in minimized structures of industrial explosive logic and detonation setters.The amount of pow-

dered explosive material on the area of 1 cm^2 of the basis equals to 0.012 - 0.615 g while the thickness of the layer equals to about 80 μm.

INFLUENCE OF DETERRENT ON DETONATIONABILITY AND SENSITIVE OF NITROAMINE FOR BLOW

N.P Loginov, G.N. Goncharova, S.N. Loginova

Samara State Technical University

The main task of our research is studying of influence of deterrents on sensitive and detonationability of thin layers of explosives. The object of this researches was NMX with additions of aromatic amins. The calculation of parametrs of ideal detonation mixctyre don' t differ from calculation for individual explosives. The difference in this situation are wide of zone of reaction and sizes of charge / 1, 2 /.

Basic formulas for calculation of speed of detonation are :

$$Dmax=D1+ \Delta D (1),$$

where is D1-max speed of detonation of basic explosives,

Δ D- increament of speed of detonation of basic explosives with density.

Dmax- maxi speed of detonation explosives .

For explosives contain organic additions or water Δ D calculate on next formula :

$$\Delta D=1.67 Co (2)$$

(results by A. Krivchenko), where is Co- speed of sound in addition.

The model for test had been prepared by press-fitting on hydravlic press on pressure 300 Mpa. On slab with hollow high of pressing on 0.05 to 2.5 mm .Our tests had been showed what NMX's high of layers is 0.7 mm, high of explosives with additions of 3% deterrent is 1.2 mm, but high of explosives with 5 % deterrents 's additions-2.1 mm. The probability of explosives on model N2 with weight 10 kg and high 25 cm had been 100 % (NMX), 56% (explosives wiht 3 % deterrent), 32 % (explosives wiht 5 % deterrent). Sensitivity is 70 mm (NMX), 100 mm (3 % deterrent), 120 mm (5% deterrent).

This fact show what product of decomposition had time to tie with chemical deterrents. The proof of participation of aromatic amine's moleculas in rapid explosive reaction was received by thin layer chromatografic, ultraviolet - intrared- emission.

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ЭКСПЕРИМЕНТАЛЬНОЕ ОПРЕДЕЛЕНИЕ ТЕПЛОВОГО ЭФФЕКТА И ТЕМПЕРАТУРЫ ИНТЕНСИВНОГО РАЗЛОЖЕНИЯ СМЕСЕЙ ПОРОШКА ФТОРОПЛАСТА С РАЗЛИЧНЫМИ МЕТАЛЛАМИ

В.Н. Лашков, В.Н. Лобанов, Н.Т. Казаковский, С.А. Климов, А.А. Селезенев, А.В. Стриканов, *Н.А. Имховик,*В.С. Соловьев, *В.В. Селиванов

*РФЯЦ – ВНИИЭФ, Саров, Нижегородская обл., *МГТУ им. Н.Э. Баумана, Москва, Россия*

Известно, что в смесевых составах на основе порошка фторопласта и различных металлов возможно протекание ударно – инициируемых экзотермических реакций [1-3]. Кинетика химических реакций, в указанных смесевых составах, мало изучена. В данной работе на основе методов термического анализа проводи-

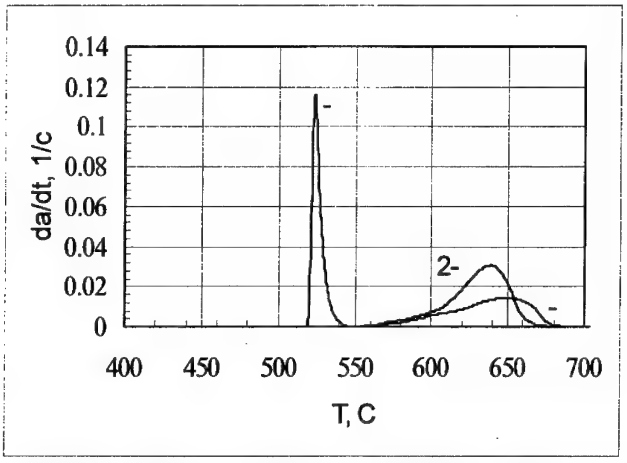

Рис.1. Зависимость скорости хиической реакции от температуры
1- C_2F_4/Ti,
2- C_2F_4/Al,
3- порошок фторопласта

лось исследование кинетики разложения порошка фторопласта и его смесей с порошками металлов W, Zr,Ti,Al. В экспериментах определял- ся температурный интервал интен- сивного разложения составов и рассчитывались кинетические константы, характеризующие зависимость скорости химической реакции от температуры. Из рассмотренных составов смесь на основе порошка фторопласта и титана оказалась наиболее химически активной. Для данной смеси экзотермическая реакция с образованием газообразных продуктов протекает при более низкой температуре, по сравнению с другими рассмотренными смесями. Реакция разложения состава протекает в узком температурном интервале ($\Delta T \cong 20K$) и носит взрывной характер. Максимальная скорость реакции достигается при температуре T_m=537 °C, рис.1.

Проведены опыты по определению теплового эффекта реакции разложения состава фторопласт/Ti. Получена зависимость теплового эффекта от массовой доли титана в смеси. Результаты опытов показали, что максимальный тепловой эффект (~4.7 кДж/г) реализуется при массовом содержании Ti в смеси 45-50%. Сопоставление расчетных и экспериментальных значений тепловых эффектов химической реакции разложения смеси позволило рассчитать конечный состав продуктов реакции. Результаты расчетов показали, что при разложении смеси C_2F_4/Ti образуются вещества TiC и TiF_3 в равном мольном отношении, а также образуется углерод и газообразный CF_4.

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ABOUT DETONATION OF AMMONIAC NITRATE SOLUTION IN THE ORGANIC ENVIRONMENT

A.L. Krivchenko, D.I. Isaev, D.A. Krivchenko

Samara State Technical University

The mechanism of detonation of liquid is not studied completely yet. The phenomenon of pulse detonation, that take place in the nitromethane mixtures diluted with acetone, is not realized in the explosive solutions of the ammoniac nitrate with hydrozinhydrate, which is near by the non-organic nature of the combustible component.

The purpose of the present work is the investigation of the possibility of detonation of ammoniac nitrate solutions in the organic liquids.

As the solution of ammoniac nitrate in the organic liquids multinuclear spirit were investigated, in particular, glycerin, in which under normal conditions (293K) 44% of ammoniac nitrate is dissolved, and while increasing of temperature it is possible to reach higher concentration of solutions. In the experiments explosive mixtures with 44% and 50% ammoniac nitrate solutions in glycerin were used. Notwithstanding the fact, that explosive heat counting of the solution mass has extremely low explosive heat (approx. 50 Kcal/kg), the solutions have stable detonation from the standard detonator and in the hard cover (steel pipes of 50 mm and 3 mm wall thickness) have detonation speed of 4000-5000 m/s. Probably, it is connected with resolving of the stoichiometric part of the solution, that is approx., 50-58% of the mixture volume. Interesting feature of the arousing of the detonation of the mentioned solution is the possibility of its initiating by the electric spark between two electrodes or with the explosion by the electric wires at the energy of the electric impulse of 500 J.Probably, this particularity of detonation of the mentioned explosive solutions is connected with the preliminary synthesis nitroether with the simultaneous ammoniac isolation, producing the gas cavities, serving to spreading of the detonation front the explosive solution.

THERMAL DECOMPOSITION OF ENERGETIC MATERIALS

S. Almada*, J. Campos ** and J.C. Góis**

Laboratory of Energetics and Detonics, Naval Explosives Laboratory, Alfeite - 2800 Almada*

***Mech. Eng. Depart. - Faculty of Sciences and Technology-*

Polo II - University of Coimbra - 3030 COIMBRA - PORTUGAL

Knowing the thermal behaviour of energetic materials is crucial to a safe production, storage, handling or even demilitarisation. The studies necessary to quantify the thermal decomposition mechanisms and kinetic, are usually complex and an extrapolation to real scale could not be acceptable. To obtain more accuracy and because many energetic materials are heterogeneous, we need to made tests with a scale higher than the classic methods but limited because safety and costs.

An original equipment was developed based in a burner fed with a mixture of propane/air and a glass column above which the sample, up to 500 mg, is placed. For a predetermined heating rate, temperature and weight variations were measured in order to time. With this equipment it was possible to characterise the behaviour after thermal initiation: combustion or explosion of different energetic materials. This has been useful to estimate the ignition temperature and delay and the kinetic parameters.

The materials selected were, for being typical cases, ammonium nitrate (AN), pentaerythritol tetranitrate (PETN), hexogen (RDX).

The developed equipment was validated with the matching results from classic termogravimetric analysis (DSC and TGA), with the kinetic approach of Coats and Redfern. With this non-isothermal method, the activation energy and pre-exponential factor were 2.10×10^{5} J mol^{-1} and 2.38×10^{17} s^{-1} for AN, 1.16×10^{5} J mol^{-1} and 1.17×10^{19} s^{-1} for PETN and 1.10×10^{5} J mol^{-1} and 4.95×10^{12} s^{-1} for RDX.

In spite of the equipment limitations the obtained results were compared with those from some other authors and seem to bee very concordant. Heterogeneous energetic materials need to be tested for each lot, so, we need cheaper ways to do it. With the equipment developed in the present work it will be possible to study those energetic materials, with lower costs.

SESSION "Shock Wave Processes in Ceramics and Composites"

Co-Chairmen:

S.Novikov - Russian Federal Nuclear Center, Arzamas-16, Russia

A.Rajendran - US Army Research Laboratory, USA

PHYSICAL MECHANICS OF DEFORMATION AND SPALLING OF CERAMIC MATERIALS

V.A.Skripnyak, E.G.Skripnyak

Tomsk State University, Tomsk, Russia

The modern computer technologies of designing of details of machines impose high requirements to adequacy of models of mechanical behaviour of materials and convenience of their realisation in algorithms. The requirement of adequacy is most important at designing ceramic products, that are loaded by shock-waves and intensive dynamic loading. The description of deformation and spalling of ceramic materials at shock-wave loading represents a complex problem in consequence of that that: a) models, constructed for metals and alloys do not reflect specifics of mechanical behaviour of ceramic materials, do not take into account distinction of reaction of ceramics under compression and tension; b) the mechanical behaviour of the same ceramic materials under static and dynamic loading can be qualitatively different; c) the mechanical behaviour of ceramic materials of one class, but with different microstructure and chemical composition can essentially differ.

The purpose of the work is discussion of opportunities of micromechanical models for the description of mechanical behaviour of constructional ceramic materials.

For computer simulation of mechanical behaviour of ceramics in details two classes of models are developed within the frameworks of approach of the physical mechanics..

Continual microdynamical models are analogue of the continuum mechanics models with internal parameters. This class of models can be used for numerical modelling and for computer simulation of deformation of solid. In these models the evolution of microstructure of a material under deformation is described with the help of change of internal parameters. For the adequate description of mechanical behaviour of ceramics it is important to set correctly equations, which describe real processes of microstructure evolution of materials during deformation. As a rule, in continual microdynamical models the non-elastic deformation of ceramic materials is considered as result of microshifts, nucleating and opening of microcracks.

Use of microdynamical models for computer simulation is obstructed by the complexity of equations, which describe physical processes of internal structure evolution in materials and by the complexity of an estimation of numerical meanings of factors of these equations. These complexities can be overcome at existence of the data of experimental tests of mechanical properties of ceramics for private loading conditions and results of study of microstructure evolution in these ceramics under deformation. Opportunities of continual micro-dynamical models for forecasting of mechanical properties ceramics behaviour in a wide range of loading's conditions are limited because of change of physical mechanisms of deformation.

Stochastic microdynamical models represent the most interest for computer simulation of ceramic materials under shock loading. In these models it is supposed, that the local mechanical properties on the meso-scale structural levels can substantially differ from the average ones. Introduction of distribution of internal parameters of model, reflecting structural non-uniformity of ceramic materials allows to estimate distribution of local parameters of mechanical state and to take into account the peculiarities of microcracks generation under loading.

Models of heterogeneous solid bodies are the most perspective for forecasting of mechanical behaviour of new ceramics, cermets, ceramic composites, ceramics with martensitic transformations. In these models a ceramic specimen or it's element is considered as system of interconnected structural elements of material. The models can be used for computer simulation of mechanical behaviour of ceramic composites with regular and stochastic internal structure. There is positive experience of using of these models for study and forecasting of mechanical properties of multiphase ceramic materials.

It is known, the technological methods which are used for increasing of strength of ceramic materials, increase or reduce of the level and structural scale of heterogeneity of ceramic materials. Structural heterogeneity of single-phase polycrystalline ceramics can be reduced in result of hot preliminary pressing and reduction of the sizes of a grain of ceramics. Degree of structural heterogeneity of ceramic materials can be increased in result of introduction in ceramic material of metallic and ceramic structural elements of various geometry and sizes, capillary dip infiltration of porous ceramics, coating of ceramic specimens by the metal and so on. The efficiency of these technological methods for increasing of strength of ceramic materials at dynamic loading is investigated poorly. Study of peculiarities of deformation and destruction of ceramic composites and polycrystalline ceramic materials with heterogeneous structure under shock-wave loading by computer simulation method showed, that distinction of mechanical properties of structural elements cause repeated many times reflection of stress waves from boundaries of structural elements. High levels of non-uniformity of field of stresses and gradients of deformation are developed on the meso-scale level of materials. In result the local tension can take place when the effective stress corresponds to compression. The received results explain the known experimental fact of increase of dispersion of

front structure in unloading waves in ceramic materials and decrease spall strength of polycrystalline and multiphase ceramic materials.

EXPERIMENTAL AND NUMERICAL STUDY OF CERAMICS FAILURE UNDER HIGH VELOCITY IMPACT

V.A.Gorelski, V.F.Tolkachev, S.A.Zelepugin

Tomsk Branch of Institute for Structural Macrokinetics, Tomsk, Russia.

Experimental methods prevail in research of behaviour of ceramics under dynamic loading and the simplified models and approaches are basically used for estimations. But analysis with use of numerical modelling allows within the framework of uniform mathematical model to investigate a process of high velocity loading of ceramic target in a wide range of the initial conditions. In the current paper both experimental investigations and numerical finite elements method is used to study peculiarities of shock wave processes in ceramic plate at impact by steel cylinder. Failure kinetic model of active type developed earlier for the simulation of various metals fractures [1] is used for numerical simulation of ceramics failure at high velocity impact. The sharp drop of strength properties at given values of specific volume of cracks [2] and specific shear energy is specified for this model.

Loading a ceramic plate of 10 mm thickness and of 60 mm diameter by steel cylinder of 7.6 mm diameter and of 25 mm length is considered. The initial velocity varied in a range from 100 up to 4000 m/s. Formation of vortex structures in ceramic plate under impact is found out and investigated. The basic factor to make vortex is the interaction of waves of pressure with opposite signs in ceramic plate. The greatest vortex development is reached in area of lateral surface of the ceramic plate. The change of initial parameters, such as the geometrical sizes or the velocity of impact, renders essential influence to formation of vortex structures. When in use a steel plate of the same sizes a brightly expressed vortex movement of a material is not observed. The vortex in the region of the lateral surface, the most expressed vortex structure in ceramics, in steel plate is not formed.

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FRAGBED2, A MATERIAL MODEL FOR GRANULATED BRITTLE MATERIAL

D. R. Curran, T. Coope, R. W. Klopp

SRI International, Menlo Park, CA, U.S.A.

This paper presents a mesomechanical constitutive model for the dynamic deformation and flow of granulated brittle material. The model treats the material as a bed of elastic blocks that dynamically slide frictionally past each other to produce "plastic" deformation. The modeling approach describes the movement of strings of interblock vacancies (macrodislocations), and is very similar to the approach taken by atomic dislocation models of plasticity in metals.

The model, called FRAGBED2, is an extension of an earlier model [Curran et al, Int. J. Impact Engng, Vol. 13, No. 1, pp. 53-83, 1993]. A preliminary discussion of FRAGBED2 was reported earlier [Curran et al, in Fracture and Damage in Quasibrittle Structures, eds. Bazant et al, E & F N SPON, 1994]. A complete description of FRAGBED2 is in preparation, both as a finalreport to the U.S. Army Research Office, which supported the work [R. W. Klopp et al, ARO Contract No. DAAH04-94-K-0001, 1 Jan. 1998], and as a submission for publication in the open literature.

In FRAGBED2, dilatancy and pore compaction are described naturally as the result of the net flux of macrodislocations in or out of a relevant volume element (RVE). The macrodislocations are driven by the net shear stress (applied shear stress minus frictional resistance) across a number of pre-specified slip planes in the RVE via the Orowan equation. The macrodislocation velocity is determined from block inertia. The blocks are allowed to undergo dynamic comminution into smaller sizes. The comminution model assumes that each block contains a flaw that has a size equal to a specified fraction of the block size. The comminution is then driven by the stress via fracture toughness relations. The comminution also causes nucleation of new macrodislocations. Rate dependence is introduced via the comminution rate and the block inertia. FRAGBED2 requires an initial block size distribution as input, which may be obtained from the initial grain size, the initial joint spacing, or from prior dynamic fracture and fragmentation calculations.

FRAGBED2 input parameters are deduced from laboratory experiments in which small explosive charges are used to either expand internal cavities in ceramic samples, or to collapse ceramic tubes. Ex-

ample hydrocode applications with FRAGBED2 are shown for penetration of long rods into Ad995 alumina confined ceramic targets at impact velocities of 1.5 and 3.5 km/s. The results are in fair agreement with experimental data [Subramanian and Bless, Int. J. Impact Engng, Vol 17, pp 807-816, 1995]. Results to date suggest that FRAGBED2 captures much of the relevant physics that govern the penetration of ceramic armor. However, additional calculations and experiments are needed to confirm this conclusion. The ceramic material properties that most strongly influence resistance to penetration appear to be the initial macrodislocation density (related to the porosity), the initial block size distribution (in some cases equal to the ceramic grain size distribution), and the intergranular friction.

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SHEAR STRENGTH OF ALUMINIUM COMPOSITE UNDER SHOCK COMPRESSION.

YU.V.Bat'kov, S.A.Novikov, N.D.Fishman and G.I.Gray III

RENC-VNIIEF, Sarov and LANL, Los-Alamos.

The resistance of structural materials to plastic deformation or shear strength along side with compressibility, viscosity and elasticity, is one of the basic reological properties of a solid, which is needed to describe its behaviour under high-rate strains, including shock waves (SW).

The paper presents data obtained by experimental study of A 359 (Al + 20% SiC) aluminium composite shear strength. The composite was provided by firm DURAL, San Diego, USA.

The shear strength characterized by dynamic ultimate yield Y_g under SW compression was studied by measurements of main stresses σ_x (longitudinal) and σ_y (transversal) which are described in detail in ref. [1]. From the viewpoint of elastic-plastic model $Y_g=\sigma_x - \sigma_y = 2\tau$ at $\sigma_x > \sigma_{HE}$, where σ_{HE} - amplitude of Hugonio elastic limit, τ - shear stresses.

By the established considerations with a 1-D deformation of elastic-plastic body in the plane shock wave:

$\sigma_x = \sigma_0 + 2/3Y_g$; $\sigma_y = \sigma_0 - 1/3Y_g$;

$\sigma_0 = (\sigma_x + 2\sigma_y)/3$; $Y_g = (1 - \nu/1 - 2\nu)\cdot\sigma_{HE}$ at $\sigma_x=\sigma_{HE}$

where σ_0 - a ball constant of the stress dyadic.

In the range of shock compression stresses from 2.3 GPa to 22 GPa, 15 tests were accomplished with 9 types of explosive contact devices of known SW parameters in the shields.

The experiment results are summed up in table where in order the following in presented: studied material, explosive loading device shield material, mass velocity U, in the shield, measured velocities σ_x, σ_y, calculated average stress σ_0, dynamic ultimate yield $Y_g=\sigma_x-\sigma_y$ and ratio σ_0/σ_x characterizing non-hydrostaticity of the stressed state of the aluminium composite behind plane SW front.

The study results have shown that the dynamic ultimate yield Y_g as the main stress difference, characterizing the shear strength of a shock compressed material and determining the shock adiabat deviation from the quasi hydrostatic compression, is almost constant and equals Y_g = 0,24 GPa for the aluminium composite in the studied range of shock compression stresses σ_x from 2.3 GPa to 22 GPa. High anisotropy of the stressed state behind SW front in the aluminium composite in the range of low stresses (σ_0/σ_x=0.9 at σ_x=2.35 GPa) decreases rather quickly with σ_x growth (even at σ_x=11.5 GPa σ_0/σ_x=0.99).

The similar constancy Y_g=const was earlier detected for ceramics [2,3].

Table

Resultant measured main stress in aluminium composite

№	Loading device		Stresses, GPa				σ_0/σ_x
	Shield material	$U_э$, km/s	$\sigma_x\pm 8\%$	$\sigma_y\pm 8\%$	σ_0	$Y_g=2\tau$	
1	CopperM1	0,098	2,4	2,0	2,13	0,4	0,89
2	CopperM1	0,175	3,6	3,3	3,40	0,3	0,94
3	CopperM1	0,18	3,8	3,6	3,67	0,2	0,96
4	CopperM1	0,22	4,9	4,7	4,77	0,2	0,97
5	CopperM1	0,35	8,5	8,3	8,37	0,2	0,98
6	CopperM1	0,47	11,5	11,3	11,37	0,2	0,99
7	CopperM1	0,52	13,0	12.8	12,87	0,2	0,99
8	Aluminium AD1	0,91	16,9	~16,6	16,70	~0,3	0,99
9	Aluminium AD1	1,15	21,8	~21,6	21,66	~0,2	0,99

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ABOUT DISTRIBUTION OF MECHANICAL STATE PARAMETERS OF CERMETS UNDER HIGH-STRAIN RATES

V.A.Skripnyak, E.G.Skripnyak, V.V.Karakulov

Tomsk State University, Tomsk, Russia

Prediction of mechanical behaviour of composites at high strain rates is one of the theoretical problems of computer designing. The aim of the work is to discuss the specific features of mechanical behaviour of metal-ceramic composites such as B_4C + Al, Al_2O_3 + Al and SiC + Al under shock wave loading. The micromechanical model of composite materials with stochastic internal structure was used for computer simulation. Results of simulation of mechanical behaviour of these composites under loading of shock waves with amplitudes of 5-15 GPa are submitted.

It has been established, the non-elastic mechanical behaviour of such composites at high strain rates is caused by the relaxation processes, proceeding on meso-scale level even though deformation of ceramic particles is elastic. Heterogeneity of microstructure of cermets composites causes the reflection of shock and unloading waves on the mesoscale level and appearance high gradients of deformation. Thus, the distribution of parameters of mechanical state on the meso-scale level is increased under dynamic loading. The pattern of the distribution of stress and strain on the meso-scale level is changing in time. Steady shapes of the distribution of stresses is achieved only after crossing of the stress wave 5-7 structural elements (ceramic particles and layers of metal). Weibull distribution can be used for describing of the steady distribution of local culculated values of stresses tensor's invariant in shock waves and release waves. Results of computer simulation showed that the difference between maximum and minimum stresses in distribution is high enough. It is important that there are distributions as pressure, so shear stresses in cermets under high strain rates.

Increase of shock pulse amplitude cause the growth of dispersion of mechanical state parameters in the volume of composites. Degree of heterogeneity of deformation is defined not only by the composites microstructure, but also by the shock pulse amplitude.

Increasing of specific volume of ceramic particles in materials with aluminium matrix increase the effective Hugoniot elastic limit of composites. The dependency of Hugoniot elastic limit from specific volume of reinforced ce-

ramic particles is not linear in a wide range of particles concentration. At shock amplitudes not above of 15 GPa the values of effective shear stresses in cermets are more high than local shear stresses in metal matrix, but lower than in ceramic particles.

NUMERICAL MODELING OF DEFORMATION AND FRACTURE OF FUNCTIONALLY GRADED POROUS MATERIALS UNDER INTENSIVE DYNAMICAL LOADINGS

A.V.Gerasimov, R.A.Krectuleva*

Applied Mathematics and Mechanics Research Institute at Tomsk State University

** Institute of Strength Physics and Materials Science, Tomsk, Russia*

The varying of the composition and the structure in the direction of spreading of shock waves may be one of the ways to influence on the shock waves formation and spreading in solids. For this purpose the content of components being a part of investigated media is to be changed in the continuous manner and according to a certain law. The value and the nature of the distribution of the materials initial porosity have the pronounced effect on shock and explosive loading process. Therefore, the porosity may also be distributed with the thickness of the construction accordingly to certain dependence.

Nowadays materials having the necessary change of properties in the preset directions represent a significant practical interest. The more so as for now, a number of technological processes allowing the manufacturing of such materials exist. They are as follow: formation of protective and strengthening coatings of powder materials (sintering, plasmic melting, gasoplasmic drifting of powders), electroimpulsive welding, selfspreading high-temperature synthesis process etc. By means of these technologies it is possible to create the multicomponents materials with fluent or fluent-discrete change of properties in the preset directions. These materials are commonly called as the functionally graded materials (FGM). If in the material the gradients of the initial porosity are in the addition to the gradients of physico-mechanical properties, then there results a functionally graded porous material (FGPM).

The technologies in order to receive FGM such as selfspreading hightemperature synthesis, electroplasmic drifting on, sintering and series of others don't guarantee 100 per cent of compactness of materials. The received materials have always the some remain property, which as a rule made worse the operational properties of FGM. The additional technological operations help to get rid of porosity, for example the shock or explosive wringing out. However to select the necessary technological routine of the present process, it is necessary to know the physical features of the multicomponents medium with porosity behavior in shock waves.

The another main purpose of this work is the development of research methods of FGPM deformation and fracture and discovery of the facts witch promote to the sound application of this materials for providing the necessary distribution stress-strain state parameters with the volume of the construction and the increase of the construction strength under shock and explosive loadings. It can be carrying out with using of computer models.

Authors have been worked out mathematical model for investigating of spatial effects of consolidation, deformation and fracture of FGPM under the influence of impulsive loading. Numerous computer experiments carried out. In the work technique of truth model calculations on direct and indirect experimental data for wide group of materials is estimated.

The system of mathematical simulation of processes of deformation and failure includes the equations of conserve for mass, impulse and energy, the equations of state of graded materials, physical equations of Prandtl Reiss and the kinetic equations of failure. This system of equations is solved by numerical methods with using of special software, which was worked by authors.

In this work are examined:

1. interaction of copper (Cu) impactor and copper (Cu) plate with gradient cover (tungsten (W)-copper (Cu)).

2. interaction of HE charge and steel (St) plate with gradient cover (iron (Fe)-tungsten (W)).

The zones of fracture and the zones of prefracture are shown in figures.

The analysis of computer experimental results showed a general rule of proceeding of thermodynamic processes in FGM. Such, it was founded, that the increasing of an initial porosity in a direction, which registered with a direction of compress piston motion under some loading regimes was very unfavorable, because such heterogeneousness of compressible medium resulted in the forming of intensive wave of rarefaction which fast moved in piston and promoted its fracture. Behind a piston FGM began to crack too. The compression of pattern in the opposite direction under those loading regimes resulted in lowering of a porosity and decreasing of a fracture. Working out of program products allowed to choose necessary technological regimes, which ensured compactness of porous FGM and conservation of integrity.

At the numerical simulation there have been used different combinations of the physic-mechanical properties and the initial porosity gradients. The results obtained have shown the possibility of FGPM use for the creation of protective coatings. The certain combinations of the porosity gradients and physic-mechanical properties of initial components allow to increase or to decrease the spall effects in the colliding bodies.

INFLUENCE OF FAILURE WAVE ON THE SHOCK PULSE STRUCTURE IN BRITTLE MATERIALS

A.V.Utkin

Institute of Chemical Physics in Chernogolovka, Russia

Under shock wave compression below the Hugoniot elastic limit the fracture of brittle materials can be produced as a failure wave that propagates on the stressed body with subsonic velocity v. Many properties of this phenomenon are well known now but some aspects are not clear yet. The question of the hour is the possibility to get information about the dynamic of failure from experimental data. That question was investigated in this paper.

The formation of shock pulse in a body under the effect of impactor was investigated in acoustic approach. Elastic wave propagates into the sample with longitudinal sound velocity. At the same time the failure wave arises on the impact surface and its velocity does not exceed bulk sound velocity c_o and is assumed as a fixed function of coordinates. It was proposed that at the front of failure wave the stresses, particle velocity and density have a jump (initial damage) and then the damage of material is described by relaxation kinetic of shear strength. Generally the amplitude of initial jump and final value of shear strength depend on coordinates. The analytical solution of this problem was found and the next results follow from it.

- Let the material be damaged instantaneously in the front of failure wave. In this case the structure of compression pulse is determined by the dependence of v on the time. At constant v the two-wave structure, caused by the failure wave following the longitudinal elastic wave, is formed. If v decreases in time the jump of longitudinal stress σ_x decreases and we can get almost smooth profile of σ_x while the transverse stress has a clear two-wave structure.

- All parameters are continuous on the front of failure wave. The main distinction of this case is the formation of spike on the front of elastic wave. Its maximum value is a constant and the duration decreases with decreasing of relaxation time τ of shear strength.

- Generally the structure of compression pulse depends on the variation of initial damage amplitude jump with the propagation of failure wave into the sample. The most interesting case takes place when the material is comminuted instantaneously at the impact surface and then the initial damage decreases. Smooth maximum forms behind the front of longitudinal elastic wave. The position of this maximum is determined by the thickness of comminuted layer λ and its amplitude depends on the ratio $c_o\lambda/\tau$, velocity v and Poison ratio.

The analysis shows that the kinetic of shear strength relaxation behind the failure wave can be derived from experimental measurements of shock pulse structure.

DYNAMIC TRANSITION OF GLASSY POLYMERS TO THE HIGH-ELASTIC STATE

L.V.Volodina, E.V.Zotov, G.B.Krasovski, S.A.Novikov, A.M.Cheverikin, and N.N.Gerdyukov

Russian Federal Nuclear Center - VNIIEF, Arzamas-16,Russia

Numerical and experimental investigations into the dynamics of viscoelastic properties of structural polymeric materials have found glassy polymers to show abrupt change in their viscoelastic behavior. The behavior of viscoelastic hemispherical loose-edged shells was investigated under a loading shot by the explosion of a microscopic quantity of liquid High Explosive (HE) in the center of the hemisphere. The design details of the loading setup and the data on pressure shot are described in [1,2]. The experiments measured shear strain on the enter hemisphere surface, $\varepsilon(t)$, using an automated strain-gage system. Experimental data processing included spectral analysis of the resulting curves to evaluate Young's modulus and calculation of the decay factor for viscosity evaluation. The results obtained were compared against the solution of a free oscillations problem for viscoelastic spherical shell in axially symmetric geometry.

Hemispheres of different materials were tested in a range of thickness ratios. The tests have shown variation in the oscillation frequency, which is unpredictable by linear viscoelasticity theory. In order to understand where this phenomenon comes from, there have been numerous experiments done in two series. The one included comparative tests with loading the samples of glassy amorphous polymethylmetacrylat (PMMA) by varied amounts of HE at room temperature and temperatures above the glass transition point of this material. The other series involved experiments using an alternative material, for which purpose optical glass (crown) was used.

Fig.1 shows time-dependent latitudinal strains, as measured near the equator by the same gage during three tests with PMMA semisphere (inner radius is 55 mm, external radius is 60 mm) using different HE weights ($m_1<m_2<m_3$), at 20°C temperature. With the clear evidence of the changed oscillation pattern in test 2 and the much more rapid transition to the next frequency under higher loading in test 3, there may be no doubts about changes in the physical and mechanical properties of material. This is equivalent to Young's modulus decreasing by two orders of magnitude. Also, the logarithmic oscillation decrement is to change significantly.

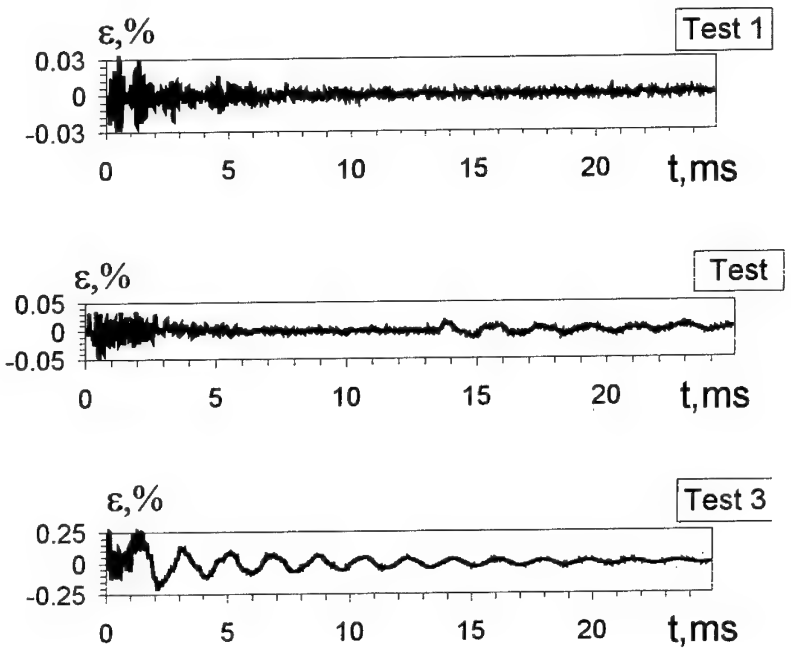

Fig.2. Dependences of latitudinal strain on time ε(t), recorded in three tests with PMMA semisphere (R=5.75 cm, h/R=0.09) using different HE weights ($m_1<m_2<m_3$).

The optical glass kept elasticity both during the test and from test to test. The logarithmic oscillation decrement was invariable too ($\Delta=0.0045\pm0.0001$). The most important observation from the crown hemisphere testing is the evidence that this optical glass, as opposed to PMMA, shows stability in elastic properties and no damping effects. While the hemispherical shells of PMMA and crown were comparable in size, and tested under identical conditions, but showing different behaviors, we may claim that organic glass has its viscoelastic properties alter because of the material changing in state physically due to the dissipation of elastic energy of oscillations. This phenomenon is what may cause accidental damage of polymeric structures by vibration or shock effects.

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SCALE EFFECT DURING DYNAMIC DESTRUCTION OF BRITTLE AND VISCOUS MATERIALS.

V.A.Ogorodnikov, A.G.Ivanov, V.I.Luchinin.

Russian Federal Nuclear Center-VNIIEF.607190, Sarov(Arzamas-16), Russia.

The paper presents results obtained by e[sperimental research of spall strengths of samples from lead (C1), cooper (M1), steel (12X18H10T), titanium (PT-3V), and metal ceramics (Al+20%SiC) as representatives of viscous and brittle materials at 5...10 times change of their scales [1,2].

It is shown that at conditions of one-dimensional high-velocity strains $\varepsilon=10^3...10^5 s^{-1}$ for all investigated materials destruction of large-size samples occurs at lower values of maximum tensions σ_p, but at higher reserve of elastic energy in samples before destruction. This causes more damage of sample material in the vicinity of plan spall. Destruction energy, specific per unit of surface is increasing function of time of tensions action of type $\lambda=2\gamma_0(\tau/\tau_0)^m$, where $\tau_0=10^{-13}s$, $2\gamma_0$- energy of surface formation, m- index of a power. Taking this into account,dependence of maximum tensions at spallation on time can be presented in such a way:

$$\sigma_p^2 = \frac{2\gamma_0 E}{c\tau_0}\cdot\frac{(1-\nu)}{(1+\nu)\cdot(1-2\nu)}\cdot\tau^{m-1}, (*)$$

where ν,E- Poisson·s ratio and Young·s modulus, c- soung velocity. Values of $2\gamma_0$ and m, at which one can observe satisfactory agreement between estimations with use of (*) and experiment, are tabulated in Table.

Table.

Material	Pb	Al-SiC	Cu	Ti	Fe
$2\gamma_0 10^4$,j/cm^2	1,3	3,0	3,8	6,0	4,0
m	0,54	0,60	0,60	0,72	0,69

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ON THE BEHAVIOR OF A DENSELY PACKED COMPOSITE IN A WEAK SHOCK WAVE.

B.R. Gafarov, A.V. Utkin*, S.V. Razorenov*, A.A. Bogatch*, E.S. Jushkov

*FCDT "Souyz", *Institute of Chemical Physics in Chernogolovka*

A comparative study has been done of two materials – a densely packed composite having a rubber binding loaded with crystalline spherical granules and its simulant fully reproducing its density and Hugoniot, using the same matrix but loaded to half volume with finely dispersed components – under the action of a ~ 100MPa, 15 to 20 mks shock wave using the laser Doppler-interferometer method to measure precisely the free surface velocity.

It has been demonstrated that such wave produces one oscillation at the front in a densely packed composite while a typical Maxwell-type wave form with an initial step and subsequent smooth relaxation to the steady state is observed in its simulant. To describe these results and dissipative processes we applied the Maxwell model, the model of simple viscosity and quadratic viscosity. As this oscillation disappears once pressure amplitude is reduced we conclude that its nature is solitonic. It is shown that this quasisoliton is formed as a result of the direct elastic interactions of granules in accordance with the nonlinear Hertz law. Note that this is the first observation of nonlinear chain soliton in a real isotropic material.

Composite fracture is treated using the "nucleation-and-grow" (NAG) model. The anomalously high resistance of composite to spallation has been ascribed to the fact that composite structure allows large volume deformations without main crack being formed.

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ МЕХАНИЧЕСКОГО ДЕЙСТВИЯ ИЗЛУЧЕНИЯ НА ГЕТЕРОГЕННЫЕ МАТЕРИАЛЫ

Острик А.В., Потапенко А.И.

ЦФТИ МО, Московская область, Сергиев Посад

Рассматривается действие рентгеновского излучения (РИ) на высокопористый гетерогенный материал типа "Стивлон", представляющий собой органическое связующее, заполненное полыми стеклянными сферами с вольфрамовым напылением. Важным этапом в определении характеристик механической нагрузки при облучении является оценка оценка энерговыделения. В настоящей работе для оценки характеристик поля первичного излучения с целью детального расчета параметров энерговыделения в компо-

нентах предлагается использовать численную методику на основе метода Монте-Карло. В ней прохождение квантов представляется как последовательность событий, моделируемых на основе законов распространения излучения в гомогенной среде и статистической оценки вкладов в сферический многослойный детектор. При моделировании поля квантов переходные вероятности определяются процессами взаимодействия излучения с веществом, а начальное распределение — источником излучения. Поскольку характерные размеры элементов материала соизмеримы с длиной пробега образующихся при взаимодействии фотонов с атомами среды вторичных фото-, оже- и комптоновских электронов, важной особенностью оценки энерго-выделения является необходимость учета нарушения электронного равновесия на границе слоев, приводящего в конечном итоге к существенному изменению параметров механической нагрузки. Неравновесная доза в компонентах вычисляется на основе аналитических соотношений, связывающих характеристики потока электронов и поглощающие способности материалов.

Моделирование механического действия проводилось в приближении мгновенного энерговыделения. В случае воздействия РИ мягкого спектра (энергии квантов — единицы кэВ) происходит существенно неравномерное поглощение энергии в наполнителе. Поскольку характерное время выравнивания температурного профиля в наполнителе по угловой координате составляет единицы миллисекунд, что, по оценкам, на два-три порядка превышает время протекания механических процессов, имеет место значительный разогрев облучаемой стороны сферы. В результате происходит сублимация или плавление части наполнителя, продукты сублимации локализуются в полости сферы, что приводит к релаксации напряжений и снижению импульса давления.

При действии РИ жесткого спектра (энергии квантов — десятки кэВ и более) значения поглощенной энергии на облучаемой и теневой стороне наполнителя отличаются незначительно и, как показывают оценки, в материале образуется несколько характерных зон. В первой зоне все компоненты полностью испарятся, поры сравнительно быстро схлопнутся и при разлете газового слоя сформируется импульс давления. Во второй зоне образуется многофазная смесь компонентов и в результате закрытия пор давление в этой зоне первоначально срелаксирует до сравнительно низких значений. В третьей зоне под действием теплового давления произойдет разрушение хрупкого наполнителя и этот слой в пер-

вом приближении будет представлять собой область с низким сопротивлением на сдвиг. В последующих слоях материала по неразрушенному материалу будет распространяться ударная волна.

Для расчета механического эффекта воздействия разработана математическая модель, учитывающая описанные особенности формирования механической нагрузки.

SIMULATION OF SOLID FRACTURE UNDER DYNAMIC LOADING

Y.P. Stefanov, T.A. Russkikh

Institute of Strength Physics and Materials Science, Siberian Branch of RAS, Tomsk, Russia

The present work is concerned with simulation of dynamic solid fracture. The calculation technique and the computational results for certain modelling problem are presented.

A set of equation for the mechanics was solved by finite-different method for two-dimensional case. According this technique fracture processes are considered taking into account the appearance of material discontinuities. The cracks are simulated in an explicit form by splitting the computational grid nodes.

The integral fracture criterion based on the principle of damage addition was used as measure of medium damages. The addition of damages is realized along the boundaries of a calculation cells that are considered as certain objects providing the material continuity. Damage and eventually failure of these boundaries results in opening of discontinuities.

The least possible size of a crack is the length of the boundary of a unit calculation cell. All smaller damages do not influence the response and properties of the material and added up to a certain magnitude. Further, the unit fracture act takes place and the crack propagates to the next node of the computational grid. The direction of crack growth is determined by the integral criterion. Its value is calculated for each computational time step and for the calculation cell boundaries. In this way, the generation of new free surfaces is performed by splitting the Lagrangian computational grid nodes along cell boundaries. Medium response in the interior of cells is described by the elastic plastic model of solids.

THERMAL PRESSURE GENERATION IN A HETEROGENEOUS MATERIAL AS A RESULT OF NONEQUILIBRIUM ENERGY DEPOSITION IN COMPONENT PARTS.

B.R. Gafarov, V.P. Efremov*, D.N. Sadovnichii

*FCDT "Souyz", *HEDRIC IVTAN*

A model describing thermal pressure generation in a composite material due to pulse heating has been proposed. The model utilizes a pressure averaging procedure with compressibility dependent weighting factors and allows one to account for an arbitrary structure of the composite and the real energy deposition on a microscopic scale as well as to obtain the optimum concentration of the absorbing component. Uncertainties have been indicated and corrections arising from the nonequilibrium character of the process and the energy losses sustained during component deformation have been computed. It has been shown how to account for the heat transfer and dissipative phenomena.

It was established that the pulse and slow isochoric heating even in the absence of heat transfer and dissipative properties of component materials would result in the appearance of varying thermal pressures due to nonequilibrium relaxation in a cell. A measure of dissipative properties of composite during pulse heating seems to be the relationship between component moduli of volume compressibilities with due account of their volume fractions rather than the dissipative properties of the component materials themselves.

Accurate Monte-Carlo calculations of energy deposition microstructure (secondary electrons taken into account by using individual collision scheme) have been carried out for two characteristic cases: an intense electron beam and soft X-ray pulse from a big explosion.

The adequacy of the model has been verified by direct experimental determination of effective Gruneisen coefficient of a composite similar to composition to real shielding materials as a function of loading content.

BALLISTIC IMPACT DAMAGE OF S-2 GLASS REINFORCED PLASTIC STRUCTURE ARMOR

Shun-chin Chou

Army Research Laboratory Aberdeen Proving Ground, MD, USA

Different sizes of S-2 glass fabric-reinforced plastic laminate plates were tested ballistically by impacting the plates with two different sizes of fragment simulating projectiles at various velocities below the limiting velocity of perforation. The impacted specimens were examined

with computed tomography to determine the extent of damage in the specimens, then those specimens were tested in compression until failure. The correlation between the failure load and the extent of damage in terms of average damage fraction was presented and discussed.

SHOCK WAVE BEHAVIOUR OF HOLLOW GLASS MICROBALLONS-POLYESTER MATRIX COMPOSITE MATERIAL

J. Ribeiro, I. Plaksin, J. Campos, R Mendes, J. Góis and V. Efremov*

Lab. of Energetics and Detonics, Mechanical Eng. Department
Fac. of Sciences and Technology, University of Coimbra, 3030 COIMBRA, Portugal
**High Energy Density Research Center, Russia Academy*
MOSCOW - RUSSIA

The porous composite materials have found a wide application for the attenuation of shock waves as absorbers of elastic shock energy. A new composite material (CM), glass+gas+polymer binder, i.e. polymer bonded hollow glass microballons (HGMB), with components which are very different on their physical and mechanical proprieties, represents a considerable promise for the shock absorption application. An essential feature of such CM is the possibility to control, in wide limits, pre-selected properties such as porous sizes and concentration, defined by the amount and the type of HGMB, as well as the concentration of the heavy fraction of the CM, the polymer binder and glass, determined by the microballons glass walls and the properties of the polymer binder.

The possibility to control the rheology of this type of CM makes them suitable not only to the study of the EoS of porous materials but also to the investigation of the dynamics strength effects under shock loading.

Results are presented about the shock wave behaviour of such CM, in this particular case using HGMB and a polyester binder in different mass ratios, on the pressure range of 0.05-10 GPa.

The selected HGMB were the Q-CEL 300 with a mean gas cavity diameter d_{50} = 92μm, a granulometric distribution from d_{10} = 20μm to d_{90} = 158μm, a glass wall thickness of 1.0±0.2 μm and an effective density of 220 kg/m^3. Different values of the CM density were achieved by the variation of the HGMB/Polymer binder mass ratio. Samples with dimensions of Ш 60Ч20 mm in the HGMB/Binder mass ratios of 0.05, 0.10 and 0.20 were tested. This CM can be seen as a three components material in which the spherical pores are

separated by a glass-polyester-glass wall with typical thickness values of δ_{glass} = 1.0±0.2μm and δ_{binder} = 0.1mm

The explosive plane wave generators, used to the shock loading of the samples, allow the sustain of a constant pressure level during from 1 up to 2 μs. The pressure history P(t) in the sample loading and release processes were registrated by manganin gauges. The samples relative attenuation index (the absorption degree of the shock compression kinetic energy) is evaluated by the crater sizes dented in Al plates and by manganin gauges analysis.

The process of shock wave propagation into samples has been registrated quasicontinuously, through each ≈200μm, by thin multifibre optical strip formed on 80-90 independent channels and connected directly to a fast streak camera (Thompson TSN 506N). This method allows the recording of the shock front propagation, the shock wave structure behind the shock front and also, in specific cases, the pulsing regimes of shock wave propagation.

Shock wave behaviour of CM has been numerically simulated by methods described in /1,2/, using the continuum matter model /1/ and the model of phonon interaction /2/. The obtained results allow the distinction between the different shock waves attenuation regimes, into the samples of different morphologies, and turn more understandable the mechanisms of shock compression energy relaxation, on the macro level, as well as the optimisation of the porous barriers attenuation proprieties.

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SESSION "Equations of State and Phase Transitions - I"

Co-Chairmen:
N.Kalitkin - Institute for Mathematical Modelling, Moscow, Russia
L.Chabildas - Sandia National Laboratories, Albuquerque, USA

EQUATIONS OF STATE IN MATHEMATICAL MODELS OF CONTINUOUS MECHANICS

V.F.Kuropatenko

Russian Federal Nuclear Center - VNIITF, Snezhinsk, Chelyabinsk region, Russia

The system of conservation laws for mass, momentum and energy is closed by evolutionary equations for processes taking place in a substance and equations of state (EOS) describing the materials properties in stable state. Wide range of physical states and, hence, wide range of variation of pressure P, temperature T and other thermodynamical parameters is typical for many applied problems (managed thermonuclear fusion, development of antimeteoroid protection for space crafts, accidents in nuclear reactors, etc.). EOS should describe material properties with sufficient accuracy in wide range of P,T.

A semiempirical approach for EOS construction is considered in the work, where the form of one of thermodynamical potentials is stated using theoretical conception and experimental data are used to determine numerical values of coefficients in these dependencies. Such approach allows to use experimental and calculational information and gives an opportunity to construct EOS in compact form convenient for numerical calculations. Mathematical models for nonstationary numerical processes impose on EOS requirements of their effective including in computations. Caloric EOS with regard to pressure P, density ρ, internal energy E and thermal EOS with regard to variables P, ρ, T are considered. Conceptual issues of EOS constructing, general issues concerning the totality of EOS and particular EOS of metals, rocks, plastic materials and explosives are presented in the work. EOS comparison with theoretical models and experimental data are given.

A special consideration is given for phase transfer description. On the phase boundaries many thermodynamical parameters are discontinue (sonic velocity, heat capacity, compressibility, etc.). These discontinuities are the sources of finite errors. To eliminate them one should modify difference conservation laws. The ways allowing to restrict the error while simulating flows with phase transfer are considered.

APPROXIMATION POTENTIAL PRESSURE RELATION DERIVED FROM GENERALIZED GRUENEISEN ACTOR FORMULA

L. F. Gudarenko, S. N. Pryalov

Russian Federal Nuclear Center – VNIIEF, Sarov, Nizhni Novgorod region, Russia

Construction of semi-empirical equations of state of condensed media involves the problem of selection of an efficient analytical form for description of the potential pressure-density relationship. About two tens of various analytical formulas are currently used for this purpose. Some of them are of a formal form. However, as a rule, it is possible to describe a wider density range even with a less number of free (adjustment) parameters making use of relations reflecting physical notions of media behavior at compression.

A formula is known for computation of the Grueneisen factor by the potential pressure function which is an extension of three models of lattice atom interaction. From this formula a potential pressure relation is obtained as a power series with integer exponents. This series is with alternative signs and converges absolutely.

The derived relation and approximation with it of tabulated values of potential pressure function for four metals, i.e. copper, molybdenum, nickel, and tungsten, are studied. Approximation properties of the derived formulas are compared with earlier known relations for the same metals. The comparison showed that the derived function approximates potential pressure at the level of the best among known relations, with being superior to this in some points and inferior in regard of computation time by a factor of 2 on the average. Advantages of the formulas include a good monotone, as well as that this relation can be used to estimate the potential pressure function only knowing parameters of the Grueneisen factor dependence on density with no approximation.

INVESTIGATION INTO KINETICS OF NATURAL CEYLON GRAPHITE TRANSFORMATIONS IN SHOCK WAVES

Yu.N. Zhugin, K.K. Krupnikov, V.I. Tarzhanov

Russian Federal Nuclear Center–All-Russian Research Institute of Technical Physic, Snezhinsk, Chelyabinsk region, Russia

.On some peculiarities of graphite compressibility in shock waves. Structural and kinetic factors. In the present work two series of own experiments have been performed with respect to the investigation into the peculiarities of pressed

Ceylon graphite and his mixture with fluoroplastic compressibility in shock waves with their amplitude in the range from 10 to 40 GPa by the method of reflection [1]. Dimensions of samples, conditions of their loading, other methodical and technical methods have been analogous to those described in [2]. Experimental results obtained by us were compared in (P, V) – coordinates (Fig. 1) with the data of other authors who studied the shock compressibility of Ceylon [3], pyrolytic [3, 4] and monocrystalline [5] graphites by the reflection method The difference of adiabats at $P \leq 20$ GPa and $P > 20$ GPa is associated with kinetic factors, as it will be shown below.

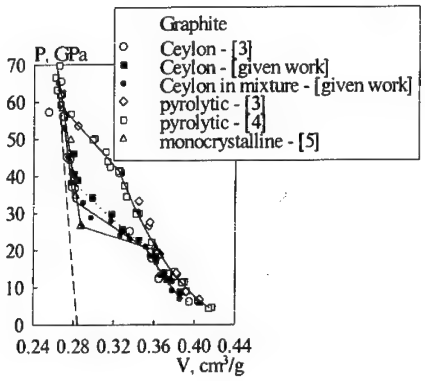

Fig.1. Graphite shock compressibility peculiarities stipulated by structural and kinetic factors.

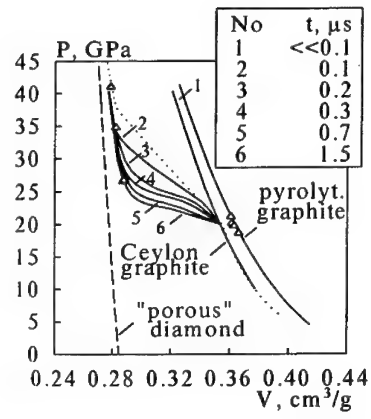

Fig. 2. (P,V) - diagram (designations - see Fig.1.)

2. Registration of graphite electric resistance changes in shock waves. The results of the first observations of "dielectrization" of natural graphites in shock wave have been set forth in [6, 7], pyrolytic graphite – in [8]. In our experiments [7] relatively thin plates with dimensions 30×2×(0.1–0.6) mm have been made from the pieces of natural Ceylon graphite with its initial density equal to 2.22 ± 0.01 g/cm^3. The range of investigated pressures amounted to ~10–40 GPa, duration of registration was equal to ~1.5 μs. It can be seen from [7] that the graphite plate resistance is sharply decreased by a factor of ~3.5 when loading by pressures P =9.1–20.4 GPa (during $\Delta t \leq 0.1\mu s$) and remains to be essentially constant during the whole time of the registration. At $P \geq 22.5$ GPa after the sharp decrease of resistance (that is also revealed at lower pressures), its marked increase taking place at $P \geq 23.2$ GPa in two stages is observed. At first the stage of relatively quick increase in resistance is seen, but then the stage of its more slow growth is noted. The first stage duration decreases with the growth of pressure from ~1 μs at P = 23.2 GPa to < 0.1 μs at P = 40.3 GPa. The attempt has been undertaken to associate the measured values of the graphite plate resistance R(t) with the volume concentration θ(t) of diamond–like phases in the shock–compressed graphite with taking into account the super fast transformation of the rhombohedral component of Ceylon graphite into cubic diamond. For assessments the model of two–component heterogeneous system with the chaotic distribution of components [9] has been used.

At the same time it has been considered that the diamond–like modifications are isolators. For obviousness, some curves among the dependencies θ(t) corresponding to different loading pressures (P = const) have been transferred to (P, V) – diagram (Fig. 2) illustrating the rate and the regularities of the Ceylon graphite transformation into diamond–like modifications under conditions of its shock loading by specified pressure P. The method of mixtures [10] was applied for the determination of specific volumes corresponding to given pressures P.

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PECULIARITIES OF PHASE TRANSFORMATIONS IN THE AL-4 % TI ALLOY IN SPHERICAL STRESS WAVES

E.A. Kozlov, I.G. Brodova *, D.V. Bashlykov *, E.V. Abakshin

*Russian Federal Nuclear Center – Research Institute of Technical Physics, Snezhinsk, Chelyabinsk region, *Institute of Metals Physics, UB RAS, Ekaterinburg, Russia.*

The state of two spheres of Al-4 % Ti alloy after their loading by spherical shock waves [1-3] of different intensity has been studied by metallophysical methods. It has been shown that the realized modes of the spheres loading have provided the melting of material in stress waves at deep radii. The melting region size depends on the loading mode. In the solid-state transformations region, depending on the radius of the analyzed layer location, the structure of compressed spheres material is regularly changed. If the external layers of the compressed and recovered spheres have remained in solid state, then the more deeply located layers (in the region of the melting start) have melted on the isentrope [3], i.e. at decrease in pressures and temperatures after the shock compression of material in the converging shock wave and in the diverging one being reflected from the sphere center. When the sphere has undergone loading by the impulse of the greater amplitude and duration in the spherical layers located still more deeply the melting of the Al-4 % Ti has been realized just at the spherically converging shock wave front [3]. At unloading of the shock-compressed melt into central cavity being formed behind the front of the spherically diverging shock wave reflected from the sphere center the vaporization of the melt took place. In the process of the subsequent cooling of the compressed and recovered sphere the vapour condensation and the shock melt crystallization have proceeded [1-3].

The size, the volume concentration, the crystalline structure of the intermetallic compound of Al_3Ti and their change along the radius r of the compressed samples have been determined. Both in the process of the high-rate crystallization and under the action of the high-strain-rate deformation in solid state, the peculiarities of the grain structure formation of α-solid solution of the alloy have been studied. In the recovered material layers adjoining to the central cavity the cast structure with the grain size of 10 μm which is less by a factor of 10 than that in the initial casting has been registered. Additionally to [4], TEM-investigations of the internal structure of the aluminum solid solution have been studied, and its evolution depending on the high-strain-rate deformation and temperature has been discussed.

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PROPERTIES OF LIQUID KRYPTON AT SHOCK COMPRESSION UP TO 100 GPA.

Glukhodedov V.D., Kirshanov S.I., Lebedeva T.S., Mochalov M.A.

Russian Federal Nuclear Center VNIIEF, Sarov, Russia

Liquefied inert gases, having high initial density and optical transparency, are convenient object to research properties of closely packed substances at high pressures and temperatures. Recorded structural transitions in liquid xenon /1-4/ attract additional interest for research of other gases - argon /5-7/ and krypton, which have not been earlier studied in area of high pressures and temperatures. This paper presents results of experimental researches up to 100 GPa.

Compressibility of krypton up to density of ~ 7 g/cm^3 and brightness temperature in the red (λ=670 mμ) area of the spectrum of ~ 21000 K at pressures up to ~ 90 GPa was simultaneously measured in experiments. This allowed to obtain thermodynamicly complete information on the state of liquid krypton. Also absorption and reflection of light in layer of shock-compressed substance were additionally studied.

Growth of shock waves front luminescence brightness in time was associated with increase of substance layer thickness, compressed by shock wave with averaged coefficient of absorption, which reached ~300 cm^{-1} at pressures up to 50 GPa in the red (λ=670 mμ) and violet (λ=430 mμ) areas of the spectrum.

The coefficient of light reflection from the shock wave front of ~8% and the brightness temperature of ~25000 K were first measured at pressure of ~80 GPa in the violet area of the spectrum.

With use of the x-t diagrams method additional experimental information on sound velocity up to 5.5 km/s behind the shock wave front was obtained at pressures up to 80 GPa.

Specific electric conductivity of liquid krypton of ~5·10^4 (ohm m)$^{-1}$ was measured at pressures up to 100 GPa. Zone of exponential dependence of electric conductivity on temperature, typical for behaviour of amorphous semiconductors, was recorded. From approximation of experimental dependence

of electric conductivity on reverse temperature (1/T) the width of the forbidden zone in shock-compressed liquid krypton (13.2±1.4) eV was determined.

Measurement of thermodynamic, optical and electrica-physical characteristics in the states with high concentration of energy is greatly important for construction of equations of state, allowing to predict properties of substances in the area of high pressures and temperatures.

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MEASUREMENT OF SHOCK RESIDUAL TEMPERATURE IN STEEL WITH THE HELP OF PHASE TRANSITIONS IN ZIRCONIUM AND TITANIUM

A.M.Podurets, A.R.Kutsar

Russian Federal Nuclear Center VNIIEF, Sarov, Russia

The α-ω phase transitions in zirconium and titanium at static pressure are known for a long time and well studied. Recovering of the metastable ω-phase after unloading allows to study phase structure of zirconium and titanium in relation to conditions of shock loading.

The phase structure of recovered samples of zirconium and titanium was studied after loading by plane shocks waves up to pressures 80-320 kbars.

From the conditions of compression and unloading, P-T diagrams of zirconium and titanium and temperature stability of ω-phase at atmospheric pressure follows, that the curve of ω-phase concentration in a recovered sample versus shock loading pressure should have three parts: rise, plateau (or maximum) and consequent lowering. Such form of concentration-pressure curves ηω(P) was confirmed in experiments. Preliminary cooling of loaded ampoule with a sample to -180°C and appropriate lowering of shock residual temperature results in increase of pressure interval, at which ω-phase is recovered.

Such ∩-shaped form of ηω(P) curves indicates, that above some critical pressure P* temperature of heating, caused by shock loading in recovery ampoule (material of the ampoule - stainless steel) and, accordingly, in a unloaded sample increases so, that ω-phase decays completely. On this fact the evaluation of residual temperature is based.

The kinetics of ω-phase decay during heating at atmospheric pressure was described with the help of the Avrami equation using parameters, defined in laboratory conditions. Dependencies of ω-phase concentration on time and residual temperature in Zr and Ti samples were obtained. The analysis of these dependencies, comparison them with experimental ηω(P) curves have allowed to make evaluation of residual temperatures in recovered ampoules, which are realised in concrete conditions of experiment. Thus we put in correspondence to pressure P* the temperature, at cooling from which in laboratory conditions ω-phase decayed completely. An assumption was made that the thin loaded samples were in thermal equilibrium with a steel ampoule during its cooling.

Obtained values of residual temperature in steel 240 - 500°C in an interval of pressure 230 - 320 kbars have appeared much above than values, obtained from calculations, usually used at temperature evaluations in shock waves.

QUANTUM-MECHANICAL CALCULATION OF EQUATION OF STATE IN THE CELL MODEL

V.M.Povyshev, A.A.Sadovoy

VNIIEF, Sarov, Russia

Several approaches for accounting the electron structure influence on material properties [1]-[2] are known. However only recently some systematic estimations of the effect have been published [3].

The authors have performed accurate quantum mechanics calculations of a valence electron's electronic spectrum change in rectangular and spherical cells with the boundary condition corresponding to vanishing pulse normal to the cell surface. On these data base within the material cell model, equations were derived for elastic energy and elastic pressure depending on specific volume, equilibrium density ρ0, pressure leading to electron transition into the state with positive total energy {ionization by pressure}, etc. It is shown numerically that at $\rho < \rho 0$ attractive forces are prevailing and at $\rho < \rho 0$ repulsive forces.

Theoretical results are being illustrated by numerical calculations on uniform compression of atomic hydrogen. Potentials of developing a method for many-electron cell model are discussed.

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ON SOLID COMPOUND ELECTRONIC STRUCTURE FEATURES

B.A. Nadykto

RFNC-VNIIEF, Arzamas-16 (Sarov), Russia

The presentation gives energy values of outer electrons of an elementary atomic cell for many compounds of solids from computational analysis of experimental compressibility data. The data pertains both to compounds in the equilibrium state at ambient pressure and temperature and to various phases of these bodies occurring under high pressure in static and shock-wave experiments. The parameters are estimated and equation of state for each material phase is computed.

For compounds the solid elementary cell can contain several atoms. A simple computation is possible when the size of the outer electronic shell of one of the atoms or ions is considerably larger than electronic shell sizes of other ions. The outer electron shell is therewith in the electric field of ionic residues of other cell atoms, it experiences a certain effect of neighboring cells. In this case pressure is mainly determined by compression of the electronic shell of the largest size.

For many compounds, including quite complex, the obtained values of solid atomic state energies give grounds to consider them basing on electronic configuration of inert gases. Implementation in this configuration of the states containing various electron quantities in the outer electron shell, alongside the crystal structure, determines compressibility of a given material in one or another phase. Energy of the atomic state for oxides of many elements per one oxygen atom is 100 eV which is characteristic of stishovite (*BeO*, *MgO*, *CaO*, SnO_2, Al_2O_3, Fe_2O_3, UO_2, *ZnO*, etc.). For all of these compounds one can expect presence of neon-like states of oxygen ions in a solid cell. The same energy value is observed in high-pressure phases of CaF_2, *NaF*, and MgF_2. In these compounds one can expect the neon-like states of fluorine ions.

Under pressure new electron phases of density both higher and lower than that of the initial phase are observed. In some experiments measuring material density both during pressure increase and during pressure decrease an incoincidence of the $P(r)$ curves in these two processes (hysteresis) is observed.

The analysis made shows that for many materials at standard ambient pressure and, the more so, at compression the properties emerge relating to various electron states in a solid atomic cell. The diversity of solid electron phases is a reflection of the energy variety of the electronic excited states which are observed in spectroscopy. The difference is that in spectroscopy the energy levels of free atoms and molecules are observed, while in a solid the atom energy levels are of a fixed volume.

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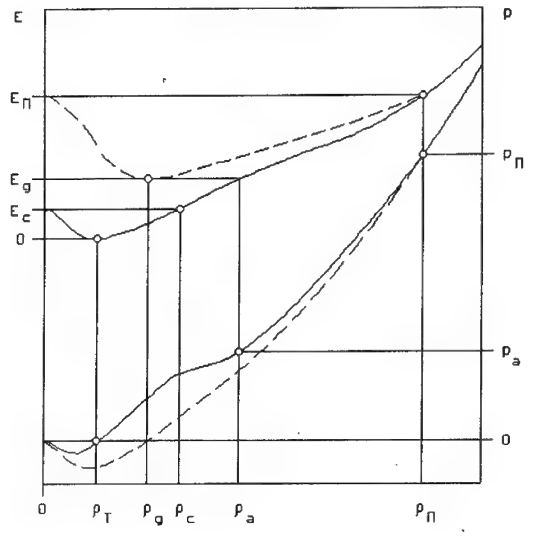
EQUATION OF STATE OF COLD HYDROGEN IN ANALYTICAL FORM

Shcherbakov V.A.

RFNC-VNIIEF (Sarov)

Basing on elementary physical notions of various states of cold(at zero temperature) hydrogen (and hydrogen isotopes) at its varying density and its reference parameters (solid hydrogen density r_T, solid hydrogen sound speed C_T, sublimation energy E_C, dissociation energy E_d and ionization energy E_u, one can find analytical expressions for pressure p and energy E as r density function: P(r), E(r),which agree within a good accuracy with modern quantum mechanics computations and experimental data. The qualitative view of the dependencies P(r) and E(r) is given in the following figure:



Here:

$0 \le \rho \le \rho_T$ - molecular rarefied phase;

$\rho_T \le \rho \le \rho_c$ - molecular condensed phase;

$\rho_c \le \rho \le \rho_u$ - molecular compressed gaseous phase (phase transition region);

$\rho_u \le \rho \le \rho_п$ - atomic phase;

$\rho_п \le \rho$ - plasma phase.

Dotted line at $0 \le \rho \le \rho_п$ - virtual atomic partially ionized phase.

THE GENERA EOS MODELS AND THE CALCULATION OF INTERATOMIC PAIR POTENTIAL FROM SPECIFIC POTENTIAL ENERGY

J.Moore, M.A.West*

*Atomic Weapon Establishment, Aldermaston, UK; * Frazer-Nash Consultancy Ltd., UK*

The Genera EOS models, being developed at AWE, will be surveyed. Progress on the determination of interatomic pair potential from specific potential energy, calculated by Genera, will be described. This is a step in the calculation of EOS for polymorphic materials.

КОЭФФИЦИЕНТ ГРЮНАЙЗЕНА И ИЗОХОРНО-ИЗОТЕРМИЧЕСКИЙ ПОТЕНЦИАЛ КОНДЕНСИРОВАННЫХ СРЕД

А.М. Молодец, М.А. Молодец, С.С. Набатов

Институт Проблем Химической Физики РАН, Черноголовка, Россия

Как хорошо известно, теплофизические свойтства, в том числе уравнения состояния вещества, можно считать установленными, если определены его термодинамические потенциалы. Одним из самых удобных термодинамических потенциалов является изохорно-изотермический, который также называют свободной энергией Гельмгольца или просто свободной энергией.

Для изохорно-изотермического потенциала конденсированных сред F(V,T) весьма практичным оказалось выражение в так называемом квазигармоническом приближении для системы независимых осцилляторов Эйнштейна. Для твердых тел оно имеет вид

$$F(V,T) = E_x(V) + 3R(0{,}5\theta + T\ln[1 - \exp(-\theta/T)]) \quad (1)$$

Для какого-либо вещества потенциал (1) считается заданным, если известны две ключевые функции - объемная зависимость потенциальной энергии $E_x(V)$ и объемно-температурная зависимость характеристической температуры θ (V,T). Если эти функции найдены, то, например, термическое уравнение состояния этого вещества определяется простым частным дифференциированием F по V

$$P(V,T) = -\partial F/\partial V = P_x(V,T) + \Gamma 3R\theta\,[0{,}5 + (\exp(\theta/T) - 1)^{-1}]/V \quad (2),$$

в котором появляется характерная для квазигармонического приближения важная функция - коэффициент Грюнайзена Г. По определению Г есть частная логарифмическая производная характеристической температуры по объему

$$\Gamma = - \partial \mathrm{Ln}\theta / \partial \mathrm{Ln}V \quad (3).$$

Роль коэффициента Грюнайзена выходит далеко за рамки только термического уравнения состояния (2) . Дело в том, что между Г и потенциальной энергией E_x существует связь. Среди ряда соотношений, выражающих эту связь, наиболее удачной представляется пионерская формула Слэтера:

$$\Gamma = - 2/3 - 0{,}5V(d^3E_x/dV^3)/(d^2E_x/dV^2) \quad (4).$$

Благодаря этому соотношению, коэффициент Грюнайзена наряду с потенциальной энергией и характеристической температурой приобрел фактически ранг третьей ключевой функции в проблеме уравнений состояния конденсированных сред. Подчеркнем здесь один особый вариант применения (4).

Заметим, что трехкратное интегрирование соотношения Слэтера (4) дает потенциальную энергию, а однократным интегрированием определения (3) находится характеристическая температура. Таким образом оказываются найденными обе ключевые функции E_x и θ, что равносильно построению изохорно-изотермического потенциала (1). Успех этой простой процедуры кардинально зависит от достоверности используемой объемно-температурной зависимости коэффициента Грюнайзена. До последнего времени в этом отношении ощущался явный дефицит, что по-видимому служило главной причиной непопулярности указанного приема построения изохорно- изотермического потенциала.

В последние годы была предложена авторская объемно-температурная зависимость коэффициента Грюнайзена

$$\Gamma = 2/3 - 2/(1 - aV_o/V) \quad (5),$$

которая позволила в полной мере реализовать нетрадиционный прием построения изохорно-изотермического потенциала твердых тел [1].

Этот же прием был использован и для описания термодинамических свойств жидкости [2], где изохорно-изотермический потенциал жидкости определялся в рамках решеточной модели (см.[3]), которая лучше всего приемлема в области высоких давлений. При этом решеточная модель дополнялась идеологией [4]. По аналогии с [4] основное дополнение в случае жидкости заключается в добавлении энтропийного слагаемого типа a_sRT в правую часть выражения для изохорно- изотермического потенциала твердого тела (1).

Общие результаты подтверждаются на примере сильного сжатия металлических (Pb, Mo) и валентных (алмаз, графит) кристаллов и их расплавов, а также ионных кристаллов (CsI) в диапазоне давлений до сотен Гпа.

Работа выполнена при частичной поддержке РФФИ (грант № 98-03-32215)

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QUANTUM-STATISTICAL HUGONIOTS OF POROUS SUBSTANCES

N.N.Kalitkin, L.V.Kuzmina

Institute for Mathematical Modelling, Moscow, Russia

Quantum-statistical model (QSM) describes adequately thermodynamics of atom with outer electron shells "broken" by external pressure so that their electrons have continuous spectrum. It provides a proper behaviour of Hugoniots for condensed and modestly porous substances at pressures from 10-100 Mbars up to 10-100 Gbars (lover figures correspond to light substances, upper ones - to heavy substances).

Detailed tables of QSM Hugoniots were calculated for more that 80 elements and simpliest compounds for porosities $1 \le m \le 10$. Simple analytic approximations were constructed owing accuracy about 0,05% for shock wave velocities and 0,3% for densities at $Z \ge 10$, i.e. not worse that accuracy of QSM itself. These approximations are recommended as reference data.

The main QSM Hugoniot for copper was treated with all published experimental points (~250). The wide-range Hugoniot was constructed which is applicable at $P \le 300$ Gbars and has unique accuracy ~ 0,1% at $P \le 5$ Mbars. It is recommended as the standard to interprete another shock-wave experiments.

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SESSION "Equations of State and Phase Transitions - II"

Co-Chairmen:

I.Lomonosov - Institute of Chemical Physics, Chernogolovka, Russia

P.Thompson - Atomic Weapon Establishment, Aldermaston, UK

MULTI-PHASE EQUATIONS OF STATE FOR METALS AT HIGH DYNAMIC PRESSURE

I. V. Lomonosov, V. E. Fortov, K. V. Khishchenko, P. R. Levashov

High Energy Density Research Center RAS, Moscow, Russia.

The thermodynamic properties of metals over a wide region of phase diagram are being studied by different experimental methods. Measurements of the principal and porous Hugoniots, as well as release isentropes, provide for a knowledge of pressure, density and internal energy. Temperature data were received recently in advanced works for shocked iron and lead and for isentropic released lead. Unlike shock-wave data, isobaric expansion (IEX) measurements allow to receive an information, which is complete from thermodynamic sense: measured at constant pressure are density, temperature, enthalpy and sound velocity. The generalization and critical analysis of shock-wave and IEX data, density measurements of liquid metal and evaluations of critical point is done with the use multi-phase equation of state (EOS). EOS for major metals were constructed along with calculation of their phase diagrams in a wide range of pressures and temperatures. Presented are results for Al, Ni, Cu, Mo, Ta, W, Pb, and some other metals. It is shown that for the most investigated metals EOS describes all mentioned above data. So the shock-wave and IEX data, as well as density measurements agree with each other. Anomalous properties of liquid Mo and W and a possible explanation of these data are discussed.

DATA BASE ON SHOCK-COMPRESSED CONDENSED MATTER PROPERTIES

P. R. Levashov, V. E. Fortov, K. V. Khishchenko, I. V. Lomonosov

High Energy Density Research Center RAS, Moscow, Russia

Shock wave studies made it possible the knowledge of information on thermodynamic properties of matter under conditions of extremely high pressure and temperature. Measurements of principal, reflected and porous shock Hugoniots and determinations of release isentrope parameters cover a broad range of the phase diagram. This unique information embraces nine orders with respect to pressure and five orders with respect to density. All of the data are unique and have their own history and present a result of difficult expensive experiments. Scientific community published a large amount of papers which contain ca. 10000 experimental points. These data have been collected and stored as ASCII files. The special procedure is developed to convert original ASCII files to SQL format. The data base containing 300 references and 10000 records is constructed. The system interface allowing on-line and e-mail access to the data base was elaborated and tested. The data base is installed on UNIX-platform with the use of SQL and Perl languages. The system interface provides for an access to the server with installed data base through WWW-gateway by address

http://teos.ficp.ac.ru/rusbank/ or http://193.233.42.5/rusbank/.

The work has been done with RBRF support by grant No. 97-07-90370.

ON ALKALI METAL HYDRIDE COMPRESSIBILITY AND STRUCTURE

B.A.Nadykto, *O.B.Nadykto

RFNC-VNIIEF, Arzamas-16 (Sarov),, SSCRF-VNIINM, Moscow, Russia*

Alkali metal hydrides exhibit quite a complex behavior under pressure. In the studied pressure range most of them exhibit phase transitions [1-3]. Hydride compressibility experimental data can be used to estimate the electron structure characteristics of these various phases (effective energy of solid atomic cell) according to model [4].

Under the standard conditions the alkali metal hydride atomic cell effective energy values show their proximity to those for the corresponding alkaline earth element. It is usually agreed that in alkali metal hydrides the charge is transferred from the metal atom to hydrogen and, hence, the ionic bond is realized. The hydride compressibility data provides the ground to infer another electron configuration where the hydrogen atom electron builds up the Cs

atom shell to the Ba electron configuration. Both the outer electrons are therewith in the electric field both of Cs+ and H+.

The energy of the cesium atom affinity to proton is 7.6 eV, the potential of ionization of the isolated molecule CsH seems to be close to the potential of Ba atom ionization, 5.2 eV. Their sum, 12.8 eV, is somewhat less than the energy of electron in the hydrogen atom ground state. The electron transfer from the hydrogen atom to the cesium atom in solid CsH and creation of the electron configuration of two outer electrons in the electric field of the Cs+ and H+ atomic core similar to the electron configuration of the barium atom may be due to the interaction with the neighboring atomic cells. This interaction noticeably increases the electron energy in the equilibrium state in the solid atomic cell. For example, for alkali metals this energy increase is by a factor of 1.4-2. At this considerable energy increase due to the inter-cell interaction it does not seem impossible that a barium-like configuration of CsH molecule outer electrons can occur. Thus, a situation can arise where the electron configuration (and the chemical bond type) will be different in the isolated molecule CsH and solid molecular cell.

The presentation analyzes compressibility data for various phases of alkali metal hydrides and compares it with similar data for alkaline earth elements. It is noted that under pressure alkali element hydrides frequently implement electronic states close to alkaline earth element states. In alkali metal hydride the phase transition from B1 to B2 structure occurs under pressure as in alkali earth metal. In the high pressure range CsH compression corresponds to compression of the elementary cell with 4 or 5 outer electrons, similar like this is observed in Ba. The difference is that in CsH the equilibrium density of this phase r=6.7g/cm3 is less than n Ba, r=8.85 g/cm3.

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AIR EFFECT ON POROUS METAL BEHAVIOR AT SHOCK-WAVE LOADING

L.F.Gudarenko, V.G.Kudelkin

Russian Federal Nuclear Center - VNIIEF, Arzamas-16, Russia

Models are analyzed designed for description of porous metal behavior at shock compression and subsequent expansion. Experimental data obtained for samples of some metals (copper, iron, nickel, etc.) of an initial density up to 20 times lower than normal in the pressure range up to ~90 Pa was used to study the effect of air in sample pores on their behavior at shock loading and subsequent isentropic expansion. The experimental data is compared with computations by several models which both do and do not take into account sample pore air effect. State regions where the models can be used considering porous samples as initial material of a lower density (without taking into account air) and those where the air effect becomes noticeable and should be taken into account are distinguished.

SHOCK COMPRESSIBILITY OF FIVE POLYMER MATERIALS AND THEIR EQUATION OF STATE AT HIGH ENERGY DENSITY

K. V. Khishchenko, I. V. Lomonosov, *M. V. Zhernokletov, *V. V. Shutov, *Yu.N.Sutulov

*High Energy Density Research Center RAS, Moscow, *Russian Federal Nuclear Center — All-Russian Scientific Research Institute of Experimental Physics, Sarov, Russia*

The equation of state of materials under the shock-wave effect is very interest for high-energy-density physics. In this paper shock compressibility of five polymer materials (high-density polyethylene, polycarbonate, polystyrene, high-impact polystyrene, polymethaphenileneisophthalamide) up to 60 GPa pressure has been experimentally investigated. The analysis of the obtained data for polycarbonate, polystyrenes, and polyamide testifies to presence of physical and chemical conversion of materials in the front which begins at the pressure of 18-21 GPa and runs at a considerable variation in medium density (about 20%) and compressibility. Similar conversions under dynamic loading attended with abrupt material compaction are characteristic of the whole class of aromatic systems which involve these polymers and are accounted for by failure of the chemical bonds of the original compound and generation of a low-compressible mixture of diamond-like carbon phase and various low-molecular components. All obtained data are used to construct polymers semiempirical equations of state for wide range of high-energy-density states,

the aromatic substances thermodynamic properties being described separately for materials before and after the conversion.

ATTRACTIVE SOFT-SPHERE EQUATION OF STATE

A. Yu. Babushkin, A.I. Lyamkin, S.T. Popov

Krasnoyarsk State Technical University Krasnoyarsk, Russia

Complete first-principles determination of interacting particles system equation of state is an unresolved problem. So the values of eight virial coefficients are determined for the hard sphere system as the most simple and theoretically investigated but they are not sufficient for the thermodynamic properties description of the whole of parameters range.

Modern calculated methods of statistic physics allow to solve the problem otherwise. Thermodynamical characteristics of the system with pair potential as hard and soft spheres, exp-6 type and other are safely defined by the Monte-Carlo and molecular dynamics methods. On the basis of these data there was suggested a number of approximative equation of state relating to the hard spheres, for example Carnahan-Starling equation for the liquid phase and Hall equation for the solid one. Equation of state taking into account attractive forces in hard spheres system was obtained at average field approaching [1]. The equation describes the corresponding model system quantitatively as distinct from van der Waals equation of state which describes it qualitatively.

In this paper similar equation of state construction is realised for the soft spheres systems. Thermodynamic functions of system with pair potential $u = \varepsilon(\sigma/r)^n$ may be expressed as functions of dimensionless combination $x = \left(p_y/p\right)^{3/n}$ where $p_y(V) = b/V^{n/3+1}$ – cold pressure in closely packed system at the same volume V. Equation of state in the unknown x takes on the form

$$Z = \frac{pV}{RT} = \frac{\varphi(x)}{1-x},$$

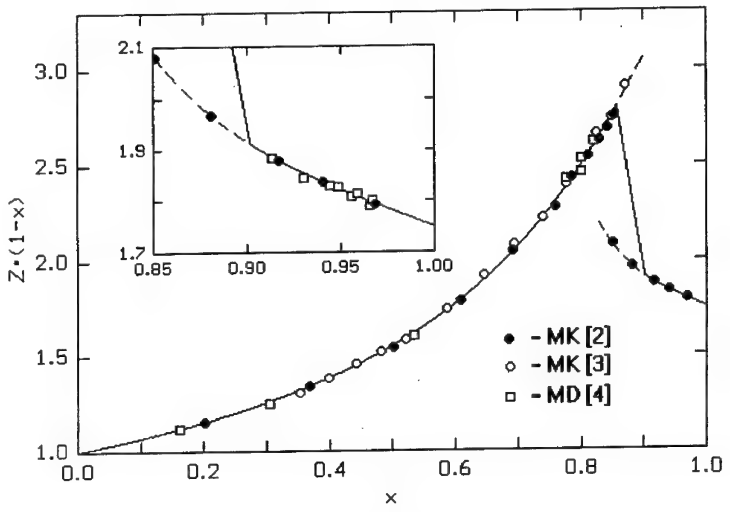
where $\varphi(x)$ – limited function with x change range (0, 1). Its asymptotic behaviour at low ($x \to 0$) and high ($x \to 1$) densities is found theoretically. Using additional data by Monte-Carlo calculation or molecular dynamics for intermediate densities, the function $\varphi(x)$ may be aproximated by proper dependence.

In this way equations were obtained for value $n = 12$

$$Z(\text{fluid}) = \frac{1-0.113238x+0.096735x^2-0.027677x^3+0.020164x^4}{(1-x)(1-0.7486147x)},$$

$$Z(\text{solid}) = \frac{1.75}{1-x}+1.411812-0.149572(1-x)+5.575065(1-x)^2+207.86305(1-x)^3$$

graphical depiction of which is shown on the figure.



At the average field approaching the attraction of the soft spheres is taken into account as follows: expression $\overline{p} = p + a/V^2$ substitutes p in definition of x, where a is a constant characterising the attraction. Isotherms of the modified equation have the van der Waals type. Compressibility in the critical point Z_C equals 0.353. More general character of attractive forces is described by the substitution p for $\overline{p} = p + a(T)/V^{\alpha}$ in the equation. The generalisation may be substantiated qualitatively. For values $n = 12$ and $\alpha = 1.8$ the compressibility Z_C is equal to 0.290, that corresponds to the critical compressibility of the majority of inert and nonpolar gases.

The proposed equation of state has an analytical form and describes the model close to reality and has attractive properties for practical application. Among them are simplicity and naturallity of definition of the potential characteristics in accordance with the experimental data (shock adiabate and critical magnitude values). Due to its properties the equation of state may serve as a reliable instrument in investigation of the detonation and other processes under high pressure.

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EXPERIMENTAL DEFINITION OF *Grüneisein*'S FACTOR FOR DECOMPOSITON PRODUCTS OF SOLID HIGH EXPLOSIVES IN A STAGE OF STRONG EXPANSION

E.E. Lin, V.A. Mazanov, A.V. Sirenko

Russian federal nuclear center - All-Russia research institute of experimental physics, Sarov, Russia

Strong expansion stage of decomposition products (DP) of TNT/RDX compositions 50/50 and 25/75 is investigated. The earlier offered method [1] for determing *Grüneisein*'s factor γ_0, which is appropriate to this stage of DP expansion, is used. The specified method consists in measurement of hydrostatic pressure P of DP in closed evacuated chamber and in the subsequent calculating γ_0 from calorical equation of state for an ideal gas. In the given work the measurements of pressure ware carried out in the closed spherical explosive chamber with inner diameter of 0,65 m, in which the spherical charges from TNT/RDX 50/50, having the weight from 190 g to 570 g were undermined. Thus average density of EP in the chamber was varied in a range $\rho_0 = 1.35 \div 4.0$ kg/m^3, and the dependence $P(\rho_0)$ had a linear kind. The valué γ_0 for DP of TNT/RDX 50/50 under expansion degree of ~10^3, established on the basis of this dependence, is equal to 0,20-0,23. The experiments with TNT/RDX 25/75 were carried out in cylindrical chamber [1]. Average density of DP was varied in a range $\rho_0 = 10 \div 40$ kg/m^3. The dependence $P(\rho_0)$ had a linear kind in the pressure range up to about 20 MPa, the speed of sound in DP within the chamber is approximately equal to 1100 m/s. The value γ_0 for DP of TNT/RDX 25/75 under expansion degree of ~10^2 is equal to 0.2.

Alongside with the data [1-4] these values can be used for specification of isentropic parameters under DP expansion in laboratory explosive devices.

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PHYSICOCHEMICAL TRANSFORMATIONS OF SARATOV CHONDRITE IN SPHERICAL SHOCK WAVES

E.A. Kozlov, Yu.N. Zhugin, B.V. Litvinov, G.V.Kovalenko, M.A. Nazarov*, D.D.Badjukov*

*Russian Federal Nuclear Center – Research Institute of Technical Physics, Snezhinsk, *V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry,RAS,, Moscow, Russia*

The experimental set–up [1] for loading of the recovered sample of Saratov chondrite (of the type L4) by spherically converging shock wave up to pressures and temperatures being unattainable in the modern static installations is described. The calculated evaluations of changes with time in pressures P(R, t) (Fig. 1) and temperatures T(R, t) realized during loading of chondrite for a number of Lagrange particles located highly $0.25 < R/R_{expl.} \leq 0.375$ and deeply $R/R_{expl.} \leq 0.2$ along the radius R are presented. $R_{expl.} = 40$ mm – the external radius of the high explosive layer. The first results of the petrographic, mineralogical and geochemical investigations into the compressed and recovered sample with initial density equal to 3.05 g/cm^3 are given.

The experiment as well as the calculation (Fig. 1, 2) gives evidence of the occurrence of three zones located concentrically along the radius r of compressed sample:

- region with the compact texture containing only rare veins of melt at $0.212 < r/R_{expl.} \leq 0.375$;
- region of the melt at $0.125 < r/R_{expl.} \leq 0.212$;
- region of the highly overheated and boiled melt at $r/R_{expl.} \leq 0.125$.

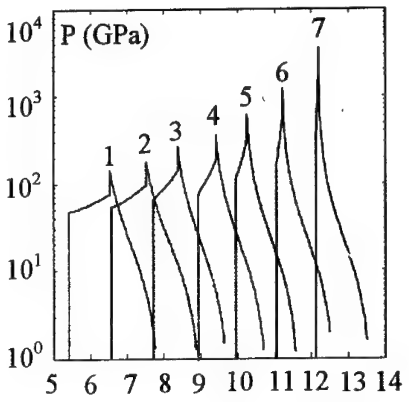

Fig. 1. Calculated evaluations of pressure as a function of time for some Lagrange particles being located deeply along the radius R in the initial full sphere. The curves 1–7 correspond to particles being initially found on the relative radii $R/R_{expl.}$ = 0.175; 0.150; 0.125; 0.100; 0.075; 0.050; 0.025. For the better obviousness the each of curves 2–7 are displaced by 1 μs to the right.

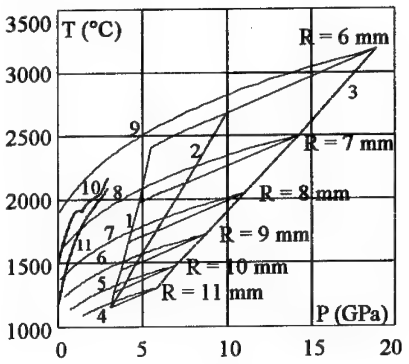

Fig. 2. Trajectories of changes in states of some Lagrange particles for Saratov chondrite which are found deeply along the radius R: 1 – Hugoniot adiabat of a single compression; 2 – envelope of states in the isentropic compression wave; 3 – envelope of states achieved in the front of shock wave reflected from the center; 4-9 – isentropes of unloading from different initial states; 10-11 – curves of melting for the Allende chondrite according to the results of the static investigations [2].

The progressive oxidation of iron and nickel is noted with decreasing r [3]. At deep radii the joint coexistance of silicate melts and metal–sulfide fluids being rich in iron is noted. Analogous sulfide fluids can be responsible for the distribution of siderophile elements between the core and the mantle of the Earth at the initial stages of its formation.

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LOADING IMPULSE AMPLITUDE ESTIMATION ACCORDING TO FELDSPAR CHEMICAL COMPOSITION CHANGES FOR IMPACTED ROCK

E.A.Kozlov, Yu.N.Zhugin, B.V.Litvinov, V.I.Feldman*, L.V.Sazonova*, A.V.Medvedev*

*Russian Federal Nuclear Center - Research Institute of Technical Physics, Snezhinsk, (Chelyabinsk -70), *Moscow State University, Geological Department, 119899, Moscow, Russia*

Experimental research of the Popigai astrobleme impacted feldspar has shown that under the action of shock waves on the contact boundaries of the plagioclase and K-feldspar grains properly oriented relative to the shock wave front the zone of the mutual migration of cations (K, Na, Ca) with the conservation of the stoichiometric amounts of Si and Al arises. The width (L) of the mutual migration zone of the Na and K cations does not exceed 300 mcm and depends on containing Ca (An %) and the impulse load amplitude up to 45-55 GPa in primary plagioclase that corresponds to the region of the solid-state transformations of minerals in stress waves.

The samples of the fine-grained pegmatite (containing 55-60 % of microcline, 25 % of quartz, 12-17 % of plagioclase An_3 and up to 2-3 % of muscovite) and of the fine-grained biotite granite (containing about 40 % of K-feldspar, about 30 % of plagioclase An_7, 25 % of quartz, 5-7 % of biotite) have been used in laboratory experiments. The ball-shaped samples, 48 mm in diameter, were placed into steel hermetic covers and were subjected to the action of spherically converging shock waves by the method described in [1,2]. The amplitude of radial stresses generated at high radii in the external layers of the balls amounted to about 20 GPa, but at the deeper radii R=1 mm its value reached 250 GPa.

As a natural analogue, the samples of AR biotite gneisses of the Popigai astrobleme from Russia have been used [3,4]. Gneisses have the granoblastic texture and contain about 50 % of plagioclase An_{29}, about 20 % of K-feldspar, 20-25 % of quartz and up to 10 % of biotite. The amplitude values of the impact load tested by samples under natural conditions have been determined by means of the quartz geobarometer [4]. Morphology of the rocks and chemical composition of its minerals after shock-wave loading were studied by SEM Camscan-4DV with Link analyzer AN-10000. In all three cases a zone of gradual transition from one mineral to another one was recorded. That takes place on the contact boundaries of the plagioclase and K-feldspar grains oriented by the definite way relative to the shock-wave front. The statistic processing of the relationship between the zone width of the mutual migration of

Na and K and the shock wave amplitude for pairs of grains whose interfaces appeared to be oriented approximately parallel with the shock wave front in the loaded and recovered samples, was presented in [5].

Thus, the estimation method of the shock wave amplitude $\sigma_{xx}=\sigma_{xx}(L,An)$ being created in the rock of the similar composition at a large-scale meteorite impact has been developed on the basis of the experimental data obtained when studying the contact boundaries state of K and Na feldspar grains in the granite samples having different primary content of Ca and undergone the shock-wave loading of the known intensity in the laboratory-scale explosive experiments.

The phenomena of the broadening of the contact boundaries of the K and Na feldspar grains when crossing the grains boundaries by shock waves with amplitudes up to $\sigma_{xx} \leq$45-55GPa (that corresponds to the region of the solid-state transformation of minerals including amorphization in stress waves) in the direction from heavy K (39 g/mole) to light Na (23g/mole) has been revealed during study into the compressed and recovered samples of rocks, and this phenomena is analogous to the stability loss of the contact boundaries between different density gases or liquids as a result of the Richtmyer-Meshkov instability development in them [6-11].

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УДАРНОЕ СЖАТИЕ И РАЗОГРЕВ ПОРИСТЫХ СРЕД *

В.Г.Щетинин

Институт химической физики, Москва

При описании ударных волн в пористых средах обычно используется предложение Я.Б. Зельдовича [1] рассматривать пористую среду как сплошную, с плотностью ρ_{oo}. Такой подход позволяет получить количественные соотношения для ударного перехода, но искажает физическую картину процесса. Если записать законы сохранения массы, импульса и энергии без использования формальной величины средней плотности пористой среды $\rho_{oo} = (1 - \varepsilon)\rho_o$:

$$(1 - \varepsilon)\rho_o D_p = \rho_f (D_p - U_f), \quad (1)$$

$$(1 - \varepsilon)\rho_o D_p^2 = P_f + \rho_f (D_p - U_f)^2, \quad (2)$$

$$E_o + D_p^2/2 = E_f + (D_p - U_f)^2/2 + P_f/\rho_f, \quad (3)$$

то величина $(1 - \varepsilon)\rho_o$ имеет смысл массы потока частиц, пересекающего фронт за единицу времени и, следовательно, в левой части соотношений (1-3) записаны аддитивные характеристики для частиц перед фронтом волны, т.е. для сплошной среды. Правая часть соотношений (1-3) также описывает параметры сплошной среды из материала частиц в конечном состоянии за фронтом волны, поскольку при давлениях выше предела прочности материала частиц невозможно существование пор в конечном состоянии с равновесными параметрами среды. Поэтому соотношения (1-3) связывают параметры состояния сплошной среды при ударном переходе из начального состояния ρ_o, а не из ρ_{oo}. С учетом условий равновесия на контактной границе с ударником:

$$P_f = P_{imp}, \; U_f = U_{imp}, \quad (4)$$

для решения системы (1-4) необходимы экспериментальные измерения величины D_p. В то же время известен механизм распространения фронта ударной волны в пористых средах, лежащий в основе модели Тувинина [2], в соответствии с которым скорость ударной волны D_p при ударе родным (из материала частиц) ударником со скоростью $W_{imp.}$ описывается соотношением [2]:

$$1/D_p = (1 - \varepsilon)/D_1 + \varepsilon / W, \text{ где: } D_1 = a + b\,U_1; \; W = 2\,U_1 = W_{imp.}, \quad (5)$$

с учетом которого система (1-5) позволяет рассчитать все параметры конечного состояния пористой среды после удара родным ударником:

$$U_f = W_{imp.} + [a+(1 - \varepsilon)D_p]/2b - \{[a+(1 - \varepsilon)D_p]^2/4b^2 + (1 - \varepsilon)W_{imp.}D_p/b\}^{1/2}, \quad (6)$$

$$P_f = (1 - \varepsilon)\rho_o D_p U_f, \quad (7)$$

$$\rho_f = (1 - \varepsilon)\rho_o D_p/(D_p - U_f), \quad (8)$$

$$E_f - E_o = U_f^2/2. \quad (9)$$

По предположению Я.Б. Зельдовича [1] закрытие пор в процессе ударного перехода происходит при практически нулевом давлении, после чего среда сжимается до конечного состояния. Такое допущение справедливо только для статических воздействий. При динамических воздействиях частицы нагружаются ударной волной и затем разгружаются в окружающие поры. Разгрузка в ограниченном объеме пор неминуемо приводит к возбуждению в каждой частице циркуляций волн сжатия и разгрузки. По этой причине, во-первых, невозможен прямой ударный переход материала частиц пористой среды в конечное состояние, на пути к которому каждая частица подвергается периодическим сжатиям и разгрузкам, а окончательное закрытие пор, возможно, происходит только в конце затухания колебаний среды. Во-вторых, между фронтом ударной волны и областью конечных состояний находится зона перехода, ширина которой определяется временем затухания циркулирующих в частицах волн сжатия и разгрузки и временем тепловой релаксации частиц. В-третьих, диссипация кинетической энергии колебаний материала частиц в зоне ударного перехода приводит к увеличению тепловой составляющей внутренней энергии и высокому ударному разогреву пористой среды.

При ударе инородным ударником на контактной границе возникают дополнительные колебания среды из-за различия жесткостей материалов частиц и ударника. После затухания колебаний ударная волна распространяется в стационарном режиме, как после удара некоторым родным (эквивалентным) ударником, скорость которого можно определить, проведя ударную адиабату родного ударника через точку пересечения ударных адиабат пористой среды из (5-8) и инородного ударника. При этом D_p описывается соотношением (5), но с заменой W_{imp} на соответствующую скорость эквивалентного ударника.

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* *Shock Compression and Heating of Porous Media,* V.G.Schetinin (Institute of Chemical Physics, Moscow)

К ОПИСАНИЮ УДАРНО-ВОЛНОВОГО СЖАТИЯ ЖИДКОГО ГИДРАЗИНА

И. М. Воскобойников

Институт химической физики РАН им. Н. Н. Семенова, Москва.

Достаточно давно [1] было обнаружено, что при разбавлении нитрометана гидразином, существенно менее энергоемким соединением, скорость детонации не только не уменьшается, но и заметно возрастает с 6.3 мм/мкс для чистого нитрометана до 7.3 мм/мкс для раствора с 0.75 по весу содержанием гидразина. Скорость детонации растворов гидразиннитрата с гидразином 79/21 только на 0.1 мм/мкс, а 30/70 на 0.8 мм/мкс меньше скорости детонации гидразиннитрата [2]. Ударная адиабата гидразина [3] близка к ударной адиабате воды, и по аналогии с данными о скоростях детонации растворов нитрометана с метанолом [1], гидразиннитроформа с водой (при весовом содержании воды 0.3 скорость детонации раствора на 1.5 мм/мкс меньше скорости детонации гидразиннитроформа) следовало ожидать заметного снижения скорости детонации при разбавлении достаточно мощного взрывчатого вещества гидразином, если он не деструктирует за фронтом волны. Кстати, при разбавлении раствора гидразиннитрат - гидразин 93.2/7.8 водой, 0.241 по весу, скорость детонации исходного раствора уменьшается почти на 0.8 мм/мкс [2].

Для объяснения указанных наблюдений были проведены расчеты параметров ударно-волнового сжатия жидкого гидразина по схемам, развитым ранее для органических соединений (см., например, [4]). При этом были рассмотрены варианты сохранения исходного гидразина за фронтом волны и его деструкции до аммиака и азота. Параметры ударно-волнового сжатия жидкого аммиака в интересующем диапазоне давлений были рассчитаны по обобщенной зависимости [5] с использованием оцененной по правилу Рао скорости звука в начальном состоянии 1.55 мм/мкс (та же величина скорости звука была найдена по правилу Рао для гидразина), ударная адиабата находится в хорошем согласии с экспериментальными данными [6].

Рассчитанная при сохранении исходного соединения за фронтом волны ударная адиабата $D = 1.55 + 2\,U - 0.0645\,U^2$ в целом согласуется с измеренными значениями (рассчитанная и построенная по экспериментальным значениям зависимости пересекаются при U = 2 мм/мкс, в эксперименте массовая скорость изменялась от 1 мм/мкс до 3 мм/мкс). Рассчитанные в предположении деструкции гидразина до аммиака и азота скорости распространения волн в том же диапазоне массовых скорос тей примерно на 2 мм/мкс больше измеренных, причем

при U = 2 мм/мкс скорость распространения волны D = 8.06 мм/ мкс, скорость звука за фронтом волны C = 6.06 мм/мкс (выполняется условие Чепмена - Жуге для стационарной детонационной волны $D = U + C$), температура продуктов деструкции около 3000 К.

Температура исходного соединения за фронтом волны, распространяющейся со скоростью 8.06 мм/мкс, равна 2010 К. Поскольку энергия разрыва связи $H_2N\text{-}NH_2$ около 60 ккал/моль, то энергия активации его разложения ожидается в 1.5 раза большей, чем для обычных взрывчатых веществ. Для детонации жидкого гидразина в разумных диаметрах зарядов нужны температуры исходного соединения за фронтом волны около 3000 К, они возможны за фронтами волн такой интенсивности, которые нельзя поддержать за счет деструкции гидразина. Однако такие температуры вполне достижимы при более быстром разложении других компонентов раствора (нитрометана и гидразиннитрата в упомянутых выше наблюдениях) при меньших температурах за ударным фронтом детонационной волны. Заметим, что измеренные скорости детонации растворов взрывчатых веществ с гидразином близки к ожидаемым из аддитивных оценок. Наблюдение деструкции гидразина за фронтом волны вполне реально и в растворах с невзрывчатыми компонентами, имеющими меньшую удельную теплоемкость, что облегчает достижение более высоких температур при равных массовых скоростях, однако измерения для таких растворов, по-видимо-му, не проводились. По результатам расчетов температуры 1500 К и 2000 К достигаются за фронтом ударной волны в гидразине при массовых скоростях 2.9 мм/мкс и 3.7 мм/мкс, а в растворах гидразина с тригидротетрафторпропанолом $HCF_2CF_2CH_2OH$ и тригидрододекафторгептанолом $H\ (CF_2)_6CH_2OH$ 50/50 по весу при массовых скоростях 2.6 мм/мкс и 3.3 мм/мкс, 2.55 мм/мкс и 3.2 мм/мкс, соответственно.

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СОСТОЯНИЯ ВЕЩЕСТВА ЗА УДАРНЫМИ ФРОНТАМИ В АЛКАНАХ, АЛКИЛАМИНАХ И ПЕРФТОРИРОВАННЫХ АЛКАНАХ И АЛКИЛАМИНАХ.

Воскобойников И.М.

Институт химической физики РАН им. Н. Н. Семенова, Москва.

Были проведены регистрации яркостей свечения ударной волны в контактирующих слоях двух прозрачных жидкостей с целью оценки оптической прозрачности жидкостей за фронтом волны и измерения температур фронта и вещества за фронтом вблизи контактных границ с оконными материалами разной сжимаемости, не теряющими прозрачность при сжатии. Результаты измерений использованы для уточнения состояний исходных соединений или продуктов их деструкции при высоких температурах и плотностях, а также определения интенсивностей ударных волн, за фронтами которых наблюдаются превращения исходных соединений. В частности, установлено сохранение оптической прозрачности, что является указанием к отсутствию деструкции за фронтом волны, жидких диэтиламина, трибутиламина, декана и циклогексана при давлениях до 18 ГПа.

При этих интенсивностях волн уточнены по изменениям яркости свечения на контактной границе подсвечивающей жидкости состояния на ударных адиабатах, которые совпали с рассчитанными в предположении отсутствия превращений и опубликованными ранее для циклогексана и декана. Пересчет пределов потери оптической прозрачности аминов и циклогексана за ударным фронтом на температуры исходных соединений дает значения 2000...2400 К. По достижении близких температур теряли прозрачность за фронтом волны по ранее проведенным регистрациям гексан и глицерин, что вполне объясняется близостью энергий разрыва слабейшей связи в перечисленных соединениях.

Были измерены температуры ударных фронтов и вещества вблизи контактной границы с оконными материалами в перфторированных триэтиламине, трибутиламине, декалине и трансформаторном масле, растворе перфторалканов. Значения температур ударных фронтов ниже 2000К совпадают с экстраполированными по давлению температурами вещества вблизи контактной границы с оконным материалом и близки к рассчитанным для исходных соединений за ударными фронтами. При больших интенсивностях волн экстраполированные по давлению к состоянию в проходящей волне температуры вещества на контактной границе с оконным материалом, как правило, превосходят температуры ударных фронтов (единственное исключение отмечено ниже) и близки к

рассчитанным при деструкции исходного соединения с образованием CF_4. Есть основания считать, что при температурах ударно-волнового сжатия перфторированных алканов и алкиламинов выше 2000...2200 К происходит быстрая деструкция их за фронтом волны. Эти температуры совпадают с отмеченными выше для потери прозрачности не содержащих фтора алканов и алкиламинов, что объясняется малым различием энергий разрыва связей *C—H* и *C—N* в рассматриваемых соединениях.

Более низкие температуры ударных фронтов при деструкции исходного соединения связаны с экранировкой со стороны фронта свечения конечного состояния слоями с неполным превращением. Это ранее наблюдалось при свечении ударной волны в сероуглероде, бензоле и ацетонитриле, причем факт деструкции исходных соединений независимо устанавливался по аномальному изменению хода ударной адиабаты или зависимости скорости звука от интенсивности волны. При диссоциации за фронтом волны галогенпроизводных метана и жидкого азота температура ударного фронта выше экстраполированной по давлению температуры вещества на контактной границе с оконным материалом из-за подсветки со стороны фронта конечного состояния менее диссоциированными слоями.

Исключение было при регистрации свечения ударной волны в перфтортриэтиламине с давлением около 22 ГПа, температура фронта, 3100 К, оказалась на 450 К выше температуры вещества за фронтом (при давлении в волне 29 ГПа температура фронта, 3450 К, на 100 К ниже температуры вещества за фронтом). Для близкого по строению и элементному составу перфтортрибутиламина температура фронта, 2450 К и 3350 К, на 250 К и 100 К ниже температуры вещества за фронтом при давлениях в волне 23.5 ГПа и 30.5 ГПа. Возможной причиной наблюдавшегося выглядит подсветка конечного состояния при деструкции перфтортриэтиламина в волне свечением исходного соединения непосредственно за фронтом волны. Скорости распространения волны с давлением 22 ГПа, 5.2 мм/мкс, соответствует температура на фронте в исходном перфтортриэтиламине около 3000 К. Для волны в перфторбутиламине с давлением 23.5 ГПа рассчитанная температура исходного соединения непосредственно за фронтом волны 2400 К. С увеличением интенсивности волны из-за уменьшения времени превращения исходного соединения подсветка и экранировка свечения конечного состояния уменьшаются, что меняет с увеличением интенсивности волны соотношение яркостей свечения фронта и вещества на контактной границе.

Работа выполнена при поддержке РФФИ, проект 95-03-09338 а.

TIME-RESOLVED WAVE-PROFILE MEASUREMENTS AT IMPACT VELOCITIES OF 10 KM/S

L. C. Chhabildas, M. D. Furnish, W. D. Reinhart

Shock Physics Applications Department, Sandia National Laboratories, Albuquerque, New Mexico USA

Development of well-controlled hypervelocity launch capabilities is the first step to understand material behavior at extreme pressures and temperatures not available using conventional gun technology. In this paper, techniques used to extend both the launch capabilities of a two-stage light-gas gun to 10 km/s and their use to determine material properties at pressures and temperature states higher than those ever obtained in the laboratory are summarized. Time-resolved interferometric techniques have been used to determine shock loading and release characteristics of materials impacted by titanium and aluminum fliers launched by the only developed three-stage light-gas gun at 10 km/s. In particular, the Sandia three stage light gas gun [1-3], also referred to as the hypervelocity launcher, HVL, which is capable of launching 0.5 mm to 1.0 mm thick by 6 mm to 19 mm diameter plates to velocities approaching 16 km/s has been used to obtain the necessary impact velocities. The VISAR, interferometric particle-velocity techniques [4] has been used to determine shock loading and release profiles in aluminum and titanium at impact velocities of 10 km/s.

Three-StageLight-GasGun: The principle of operation of the Sandia's three-stage light gas gun is briefly described here. Very high driving pressures (tens or hundreds of GPa), are required to accelerate flier plates to hypervelocities. This loading pressure pulse on the flier plates is time-dependent to prevent the plate from melting or vaporizing. This is accomplished by using graded-density impactors [1-3]. When this graded-density material is used to impact a flier-plate in a modified two-stage light gas gun, as indicated in Figure 1(a), nearly shockless, megabar pressures are introduced into the flier plate. The pressure pulse is also tailored to prevent spallation of the flier-plate. This technique has been used to launch nominally 1-mm-thick aluminum, magnesium, titanium (gram-size) and tantalum [5] intact plates to 12.2 km/s. The technique has been enhanced by using the experimental configuration shown in figure 1(b) to allow the launching of titanium and aluminum plates to velocities approaching 16 km/s [3]. This is the highest mass-velocity capability attained with laboratory launchers to date, and therefore should open up investigations into new regimes of impact physics using various diagnostic tools [4,5].

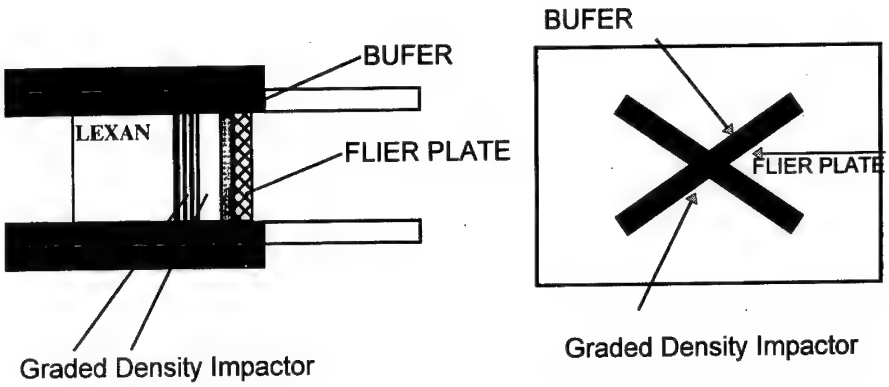
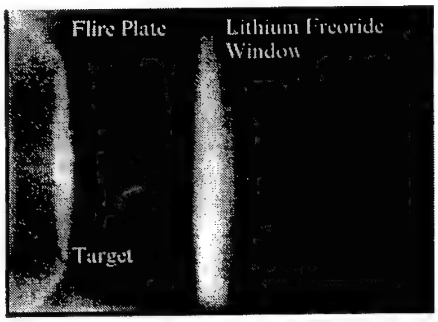


Figure (1a). The third stage configuration used to launch flier plates to hypervelocities. The Enhanced Hypervelocity Launcher, configuration, fig (1b), is used to launch confined flier plates in a tungsten barrel to velocities approaching 16km/s.

Experimental Method: We have used the three-stage light gas gun to perform one-dimensional plate-impact experiments. To achieve one-dimensional conditions, the target plate is stationed ~ 20 mm from the flier-plate. This ensures that the flier plate achieves peak particle velocity prior to impact, and remains relatively flat prior to impact.



Results: Symmetric plate-impact experiments have been performed using aluminum, titanium, and tantalum at impact velocities of ~ 10 km/s. Figure 3b shows the radiograph of an experiment in which a 0.56 mm titanium alloy (Ti-6Al-4V) flier-plate is launched at 9.6 km/s prior to impacting a 2.0 mm thick titanium alloy target. The lithium-fluoride window is seen in the radiograph in Figure 3b. The flat portion of the flier-plate prior to impact as observed in the radiograph is 19 mm. Note that for the full duration of the ex-

periments there is a free rear surface behind the flier-plate; this allows measurements of a complete release from the shocked state. As indicated in Figure 4, a velocity interferometer VISAR [4], records the particle-velocity history at the sample/lithium-fluoride window interface. The time-resolved particle velocity history measurements at the target/lithium-fluoride window interface are shown in Figure 4(a) and 4(b) for aluminum and titanium, respectively. Since no fiducial was established in these experiments, the shock arrival time at the target/window-interface is arbitrarily set to zero.

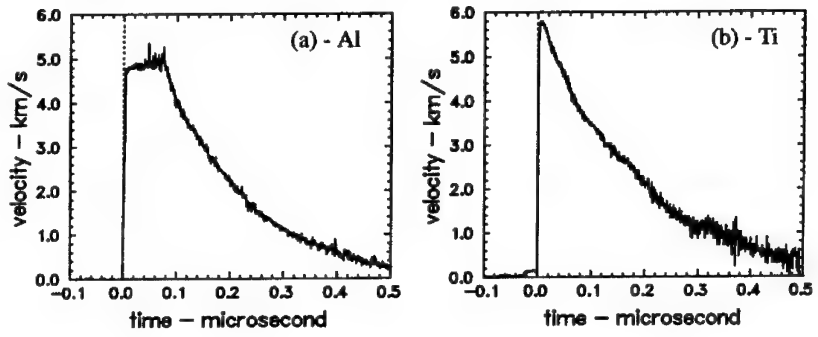
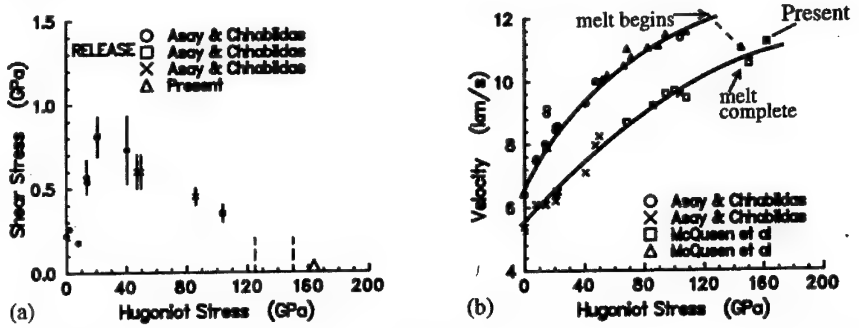


Figure (4). Measured interface particle velocity history for shock-loading and release experiments in (a) 6061-T6 aluminum at an impact velocity of 9.95 km/s, and (b) Ti-6Al-4V alloy at an impact velocity of 9.6 km/s. Symmetric impact configuration was used in both experiments.

Aluminum Experiment: Figure 4(a) depicts the shock loading and release profile in aluminum shocked to over 1.62 Mbar at an impact velocity of 9.95 km/s. In this experiment, a 0.98 mm thick aluminum flier-plate impacts a 1.98 mm thick aluminum target. Notice that a sustained shock of approximately 80 ns is observed in the figure prior to release. The titanium alloy is shocked to 2.3 Mbar at an impact velocity of 9.6 km/s, and a complete release profile as indicated in Figure 4(b) is measured. A profile resembling wave attenuation is measured in the titanium experiment because a thin flier plate (0.56-mm) impacts a thick (2.0 mm) target. Both experiments indicate a lack of elastic-plastic release structures which is a clear indication of complete melt in the shocked state. Most significantly, the results demonstrate the successful use of time-resolved velocity interferometric techniques for EOS investigations using the three-stage light-gas gun. These release profile structures will yield the off-Hugoniot states of materials shocked to extremely high-pressure.

The lack of elastic-plastic release clearly indicates complete melt in the shocked state at 1.62 Mbar. This is indicated as zero shear stress in Figure 5(a), and is consisitent with previous measurements by Asay and Chhabildas [6,7]. The Hugoniot state is based on measurements of the impact velocity and the existing equation of state for aluminum [8] given by the shock velocity (U_s)-particle

velocity (U_p) relation as (U_s (km/s) = 5.386 + 1.339 u_p). The leading edge of the release wave velocity, or the sound speed in the shocked state at 1.62 Mbar can be calculated knowing the sample and impactor dimensions, the dwell time of the shock at the sample/window interface, and the impact velocity. The calculated value of 11.24 km/s agrees quite well with extrapolation of previous sound speed measurements by Asay and Chhabildas [6,7] and McQueen *et al* [9] and is shown in Figure 5.



Figure(5). Measurements of (a) shear stress and (b) sound speed at 162 GPa in aluminum as determined from the release wave profile indicated in figure 4(a). Comparison with previous studies is also indicated.

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SESSION " Advances in Experimental Techniques "

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IMBEDDED GAUGES IN SHOCK AND DETONATION WAVE EXPERIMENTS

Paul A. Urtiew and Jerry W. Forbes

Lawrence Livermore National Laboratory, USA

Experimental study of the shock and detonation wave phenomena rely very heavily on the experimental data in general and in particular on the data obtained from gauges placed within the experimental test sample to measure accurately the local changes of parameters of the investigated material. For a complete description of these changes taking place in a dynamically loaded material one would like to know both the spatial and the temporal resolution of pressure, temperature, volume, wave and mass velocity. However, temperature and volume are not easily attainable. Therefore, most of the in-situ work is limited to measurements of pressure and both wave and mass velocities

Various types of these gauges will be discussed and their records will be illustrated. Some of these gauges have limitations but are better suited for particular applications than others. These aspects will also be discussed.

While these experiments are necessary to validate theoretical models of the phenomenon, they can also provide sufficient amount of data to yield complete information on material characteristics such as its equation of state (EOS), its phase change under certain loads and its sensitivity to shock loading. Processing of these data to get important information on the behavior of both reactive and non-reactive materials will also be demonstrated.

EMBEDDED ELECTROMAGNETIC GAUGE MEASUREMENTS IN SHOCK INITIATED PBX9501 EXPLOSIVE

R. L. Gustavsen, S. A. Sheffield, R. R. Alcon, L.G. Hill, *Craig M. Tarver

*Los Alamos National Laboratory, Los Alamos, NM, *Lawrence Livermore National Laboratory, Livermore, CA, USA*

We report recent measurements on PBX9501 explosive using the latest embedded electromagnetic particle velocity gauge techniques developed at Los Alamos National Laboratory (LANL). The magnetic particle velocity gauging technique in use at LANL was developed by Vorthman and co-workers[1-3] in the early 1980s. Numerous refinements have been implemented since then. The overall experimental configuration is shown Fig. 1. An explosive sample is prepared in two 30 degree wedge shaped pieces. A gauge membrane, described in Fig. 2, containing the conductive elements is glued between the two wedges. The 10 particle velocity gauge elements, at positions of approximately 0.5 through 5.0 mm on 0.5 mm intervals, produce voltages proportional to the local particle velocity. The "shock tracker" measures the position of the shock front as it moves through the sample. An additional single loop "stirrup" gauge is mounted on the front of the sample, parallel to the shock plane. The completed assembly is mounted on an aluminum plate and placed in a magnetic field at the end of the barrel of a 70 mm bore gas gun. A plastic projectile faced with a nonconductive material such as sapphire, aluminum oxide ceramic, or Z-cut quartz impacts the sample at a precisely measured velocity.

Figs. 3 and 4 shows the quality of data, which we obtain in a single experiment using this technique. In this experiment PBX 9501 (95% HMX, 5% binder, sample density 1.826 g/cm^3) was impacted by a high density multicrystalline aluminum oxide ceramic (Coors Vistal) at a velocity of 0.817 km/s producing an input of 5.16 GPa. Fig. 3 shows 11 wave profiles from gauges that were at depths of 0 through 5 mm in the explosive. This experiment, typical of high density pressed explosives, exhibits a combination of homogeneous and heterogeneous reactive wave growth. There is growth in the wave front (heterogeneous) and there is a reactive wave that develops behind the front (homogeneous).

Fig. 4 shows x-t trajectories obtained from the shock tracker and gauges. These data were fit to a special function from which velocity (shock or detonation) as a function of time and position were obtained. The measured run distance to detonation was 5.3 mm. The last particle velocity gauge shown in Fig. 3 was located at 4.96 mm, a location where it is just short of full detonation.

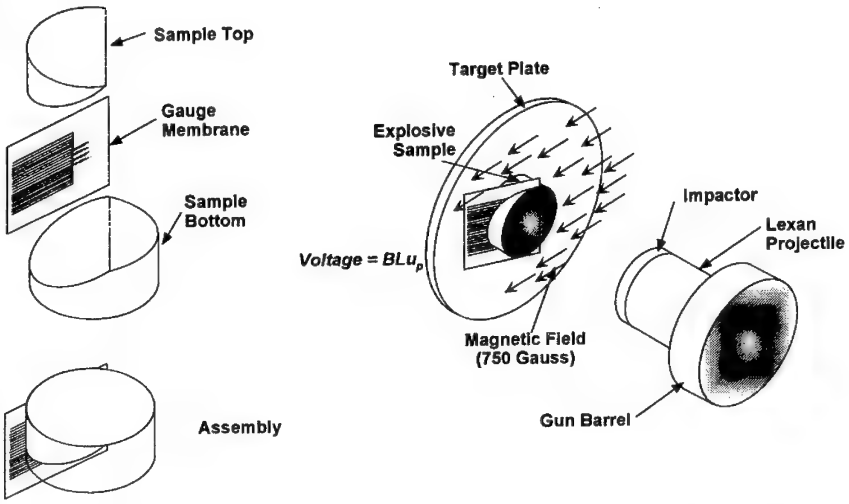

FIGURE 1. Overall configuration for making embedded gauge measurements in PBX9501 explosive. The gauge membrane containing the conductive elements is sandwiched between two wedges whose angle is 30 degrees. The completed assembly is placed in a magnetic field and impacted using a projectile and impactor launched in a gas gun.

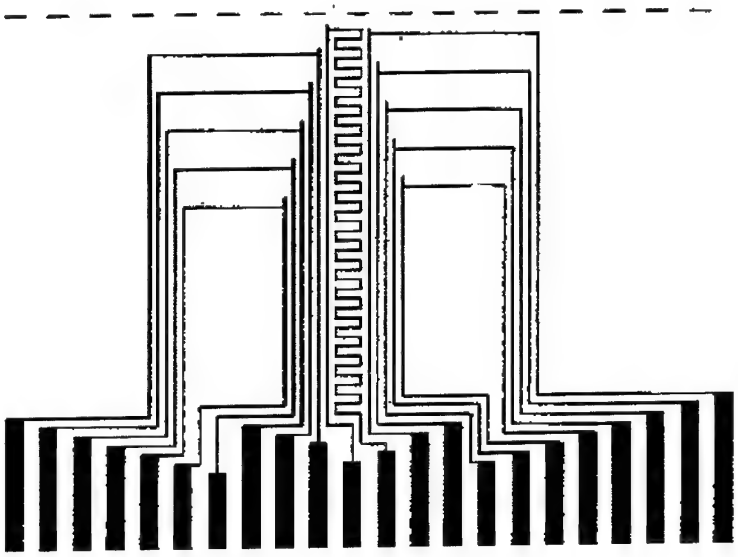

FIGURE 2. Detail showing the pattern of conductive elements in the gauge membrane. The 10 elements on the left and right are for the measurement of particle velocity. When mounted in a sample at an angle of 30 degrees, the active elements are at depths of 0.5 through 5 mm. The central element monitors the position of the shock. Gauge elements are 5 mm thick aluminum, sandwiched between 25 mm thick layers of FEP Teflon, resulting in a 60 mm thick membrane.

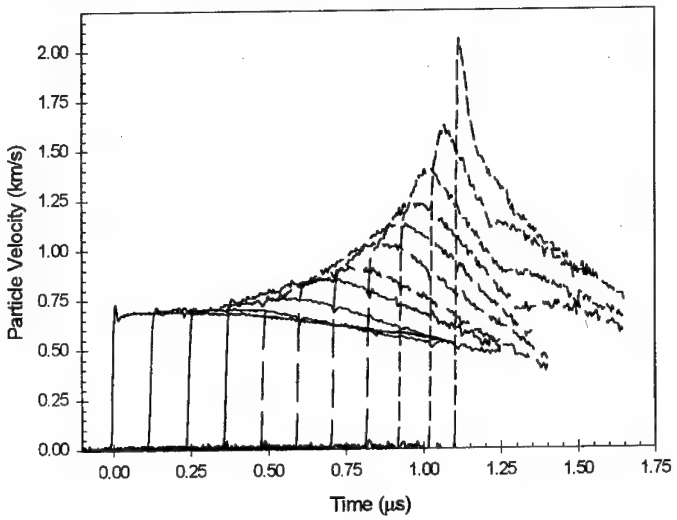

FIGURE 3. Particle velocity wave profiles from an embedded magnetic gauge experiment in PBX 9501. The input of 5.16 GPa was produced by impacting the PBX9501 with aluminum oxide ceramic (Coors Vistal) with a velocity of 0.817 km/s.

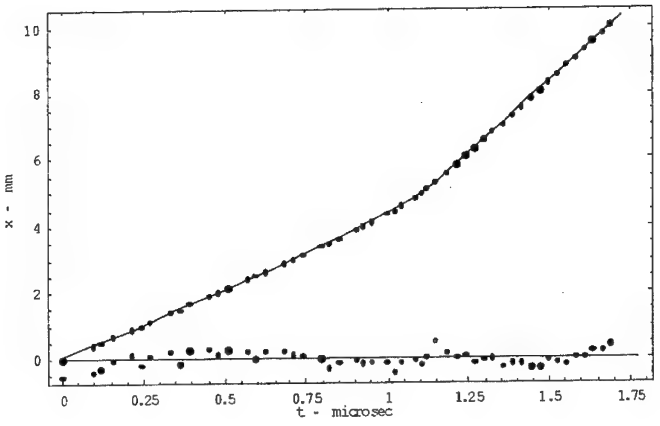

FIGURE 4. x-t data, fit, and 10 x residuals for PBX501 with 5.16 GPa input. Data is from the shock tracker and the initial rise on the particle velocity gauges. The fit indicates an initial shock velocity of 3.89 km/s, and a detonation velocity of 8.74 km/s. The run distance to detonation, determined at the point where the fitted velocity is 99% of detonation velocity, is 5.3 mm. Time to detonation is 1.16 ms.

We have recently completed a substantial number of these experiments on PBX9501 samples with differing initial densities. The results of these experiments will be highlighted. The combination of the precisely controlled impact condition, a feature of gun experiments, and the measurement technique, allows us to determine differences in initiation properties in samples differing in density by as little as 0.005 g/cm^3. Experiments are also being done in PBX 9502, which requires a two-stage gun to produce the projectile velocity required for initiation.

We are successfully modeling these experiments using the ignition and growth formalism.[4] Results of these efforts will be presented. Data such as these are valuable to us and other researchers modeling the initiation process. Tight constraints are placed on the mathematical form and the parameters used in the model.

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RECORDING OF TEMPERATURES OF SHOCK-COMPRESSED SOLIDS BY CONTACT METHOD.

G. Pesotsky, M. V. Zhernokletov, A. N. Shuikin, A. I. Samoilov, G. N. Korzenev, G.Ju.Povolodskaya.

RFNC-VNNIIEF Sarov, Russia.

Tests were performed to record temperature of polymethyl-crylate with density of 1.18 g/cm^3 shock-compressed by pressures of about 4-5 GPa using

the thermocouple method and the method of thermal resistances. Pressures of shock compression in the investigated substance were formed by plane-wave generators of shock waves basing on explosives. Thin film copper-nickel thermocouples and copper thermal resistances were used as gauges for recording temperature of shock-compressed material (PMMA) under investigation. Copper-nickel thermocouples were manufactured by sequential deposition of copper and nickel electrodes on thin dielectric base. Thickness of each electrode and thickness of dielectric base was 2-3 μm. Calibration of thermocouples in static conditions was carried out. The thermo-EDS coefficient is calculated $\alpha = 25 \mu W / {}^0C$ for Cu-Ni thermocouples. Temperature of shock-compressed polymethyl-crylate was theoretically calculated in pressure range 0÷10 GPa.

When performing tests with use of thermocouples, significant difference is recorded between form and value of thermo-EDS signals and, correspondingly, temperature in dependence on space location of gauges regarding to shock wave front. The following values of temperatures were recorded in polymethyl-crylate at shock compression pressure of 5 GPa: 950K for parallel and 620K for perpendicular configurations. Indications of thermocouples, located parallel to the shock wave front, 1.5 times exceed indications of thermocouples, located perpendicular to the shock wave front. Theoretically calculated temperature of polymethyl-crylate pressure of 5 GPa is equal to 460K.

In testes for measure of polymethyl-crylate by the method of thermal resistances we used thin film cooper gauges, which were manufactured by method of magnetron deposition and polylithography. Thickness of copper layer of the gauge was 1 μm. The following values of temperatures were experimentally obtained for polymethyl-crylate: 350K, 420K, 480K at pressure of compression of 5, 8, 10 GPa, correspondingly. Theoretically calculated values of temperatures for polymethyl-crylate were 460K, 600K, 710K at similar values of pressure.

RECORDING OF SHOCK-WAVE AND DETONATION PROCESSES BY LASER VELOCIMETER THROUGH WATER WINDOW.

A .V. Fedorov, A. V. Menshikh, N. B. Yagodin.

RFNC-VNNIIEF Sarov, Russia.

Water is a good material for recording of shock-wave processes in materials with parameters of dynamic rigidity. Thus, water is used as a window for recording of shock-wave parameters at the investigated sample-water window interface boundary. Recording is performed by laser interferometric Fabry-

Perot and ORVIS methods. The paper presents a series of experimental researches with use of water window.

To record parameters of material resistance against destruction of shock-wave loading the profile of the material-water window interface boundary was recorded. In the case of spall fracture one can observe characteristic picture of velocity profile vs. time in the form of attenuated vibrations. This picture allows to determine dynamic strength of materials, using such method the strength of some materials (Cu, Al, Fe, plexiglass) are determined at characteristic loading with tension effects time of 10^{-6}-10^{-7}.

For some practical problems the velocity increase at launching of liners into water is of all interest.

Such profiles were recorded for thin(less than 1 mm)and thick liners.

For compacting of ultra-dispersed diamonds (UDD) with density of 0,6-1,5g/cm^3 the water window was used to record profile of particle velocity vs. time for wave passed through UDD sample. At the sample entrance the shock wave had a rectangular shape.

Also the water window was used to research structure of detonation front of condensed HE.

Thin (6-10 mm) aluminium foil was placed between water and HE. Thus, the detonation front is recorded in group of mixture HE.

The paper also describes other applications of water windows for shock-wave experiments.

ИЗМЕРЕНИЕ ДАВЛЕНИЯ В УДАРНЫХ ВОЛНАХ, ВОЗБУЖДАЕМЫХ ИМПУЛЬСАМИ МЯГКОГО РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ НА УСТАНОВКЕ АНГАРА-5-1, ПРИ ПОМОЩИ ПВДФ ДАТЧИКОВ.

В.В. Якушев, В.Е. Фортов, Т.И. Якушева, *Е.В. Грабовский, *Г.М.Олейник, *В.П. Смирнов

*Институт проблем химической физики РАН, Черноголовка, *ТРИНИТИ, Троицк, Моск. обл.*

Изучение процессов генерации ударных волн при взаимодействии мощных импульсов электромагнитного излучения с конденсированными средами является одним из перспективных и быстро развивающихся направлений физики высоких плотностей энергии. Определение профиля давления в таких волнах может дать важную информацию как об интенсивности падающего на мишень излучения в конкретном эксперименте, так и о физике его взаимодействия с веществом.

В данной работе пьезоэлектрические пленки органического сегнетоэлектрика - поливинилиденфторида (ПВДФ) были успешно использованы для измерения динамического давления в ударных волнах,

возбуждаемых в алюминиевых или стальных мишенях под действием импульсов мягкого рентгеновского излучения на установке "Ангара-5-1".

В экспериментах нагрузкой генератора установки (ток до 5МА) являлся каскадный (двойной) лайнер, внешняя цилиндрическая оболочка которого, ускоренная к ее оси давлением магнитного поля генератора, конвертирует свою энергию в импульс мягкого рентгеновского излучения с наносекундным временем нарастания. Облучаемая мишень располагалась на расстоянии 8 см от источника. Амплитудное значение мощности излучения на ее поверхности составляло 2 - 5 ГВт/см^2. Конструктивно мишень была объединена с датчиком давления. При этом, для защиты от силиных электромагнитных помех, датчик был расположен в экранирующей металлической трубке и вся сборка размещена за специальным коллиматором, предотвращающим проникновение рассеянных в окружаюшей плазме токов на поверхность образца. Был также принят ряд специальных мер, предотвращаюших воздействие на поверхность мишени вторичных электронов.

В качестве материала чувствительного элемента использовали электрически поляризованную модифицированную ПВДФ пленку марки Ф-2МЭ толщиной 25-30 мкм. Плоская мишень толщиной 0,5мм имела акустический контакт с чувствительным элементом. Необходимая точность измерений достигалась как предварительной тарировкой каждого чувствительного элемента, посредством измерения пьезоэлектрического модуля d_{33}, так и выборочной динамической калибровкой датчиков в специальных взрывных экспериментах.

PVDF MEASUREMENTS OF HEAVY-ION-BEAM-INDUCED PRESSURE PULSES IN LEAD TARGETS

V. Yakushev, V. Fortov, M. Kulish, T.Yakusheva *R. Bock, *Dieter H.H. Hoffmann, *U. Funk, *M. Stetter, and *S. Stowe

*ICP RAS, Russia, *GSI, Germany.*

PVDF piezoelectric polymer shock stress sensors have been used to measure the pressure pulses generated by heavy ion beam in the GSI accelerator at Darmstadt (Germany). Total amount of 10^{10} Ar^{+18} ions with 300 MeV/nucleon was distributed in a single parabolic bunch with a duration of 500 ns. The bunch was focused on lead targets. The focal spot size was about 800 μm horizontal and 600 μm vertical. The sensors, 5 mm^2 in area, were epoxy-bonded onto lead cylinder 10 mm in diameter and covered either lead or epoxy holders. Particular attention was given to minimizing of the non-planar strain effects on gauges' output. For this purpose the gauges were made of an uniaxially-stretched PVDF film and specially oriented on the target surface. From the experimental results, time-resolved stresses resulting from interac-

tion between the ion bunch and the targets were obtained, including a determination of induced peak pressures (to 1.5 kbar).

TEMPERATURE OF SHOCK COMPRESSED CARBON TETRACHLORIDE FROM 2-BAND RADIOMETRIC MEASUREMENTS IN THE MID-INFRARED

O. V. Fat'yanov, T. Ogura, and K. Kondo

Materials and Structures Laboratory, Tokyo Institute of Technology Nagatsuta, Midori, Yokohama, Japan

High accuracy temperature data for carbon tetrachloride, CCl_4, compressed in the 4.6 to 9.2 GPa pressure range were obtained from mid-infrared radiance measurements in two overlapping bands, approximately 7 to 9.5 μm (band #1) and 9 to 12 μm (band #2). Planar shocks were generated by impacting targets with copper flyer plates accelerated to 1.1 to 1.8 km/s with a propellant gun. The shock states in the samples were determined from the measured projectile velocities and known Hugoniot adiabats for copper flyer and driver plate and for CCl_4.

Fast liquid nitrogen cooled, reverse-biased HgCdTe photovoltaic detectors with a cut-off frequency of 100 MHz at 3 dB were the principle feature of the two-channel radiometer housed in a light tight box outside the target chamber. The radiation emitted from shock-compressed liquid sample is reflected at an expendable mirror and transmitted out of the vacuum chamber through a window of barium fluoride used as a seal in the chamber wall. The radiation then is collected and collimated by two identical ZnSe lenses of 63.5 mm focal length, is split by a 50/50 broadband infrared ZnSe beamsplitter and refocused onto the detectors by two more identical ZnSe lenses of approximately 45 mm focal length. 7 - 9.5 μm and 9 - 14 μm band-pass filters mounted immediately in front of the detector windows select the radiometer wavelength range and ensure blocking of any visible light. Detector signals are amplified by matched low-noise AC-coupled preamplifiers in tandem with ultra-low noise wide band video amplifiers (350 MHz, 40 dB gain) and recorded on a digital Tektronix oscilloscope.

Black-body radiation simulator with an estimated emissivity value of at least 0.995 placed inside the target chamber in a position 180° away from the targets was used as an absolute intensity calibration source. To go from the target to the calibration requires only a 90° rotation of the turning expendable mirror. Slotted chopper located in the position of the target image focused by the first collecting lens was used to provide roughly 20 μs pulses of incoming radiation. Linearity of the system over the working range of radiant power was checked numerically using external transmittance data for all optical components and spectral responsiv-

ity curves for the detectors. Maximum relative deviation from the linearity for computed detector output signal did not exceed approximately 1 and 2 % for band #1 and #2, respectively, for all calibration temperatures except 500 K when the signal-to-noise was as low as 2÷3. The exit aperture of a black-body radiation cavity was made equal with a high accuracy to the aperture of the liquid sample target. Any other arrangement resulted in large systematic radiometric errors due to background collection by 60° field of view detectors that have been revealed in thorough preliminary tests.

High precision infrared absorption spectra for BaF_2 windows and CCl_4 were measured on a Perkin-Elmer model Spectrum 2000R NIR FT-Raman spectrometer. The measurements cover the range 4000 to 450 cm^{-1} at 0.2 cm^{-1} steps. No any traceable impurities were resolved in the liquid samples spectra.

The temperature is found by the least-square fitting of time-resolved radiance data to the solution of the radiation transfer equation after the shocked material becomes opaque. Transmittance of the target window and time-dependent absorbance of unshocked CCl_4 layer that have not been accounted automatically in the calibration procedure, are included in this numerical procedure. The lower temperature limit was determined assuming non-reflecting shock front. According to the published experimental data, the maximum reflectivity value in the visible does not exceed roughly 1 % under our experimental conditions. This assumption may be completely wrong in the infrared, so another data set was calculated for the reflectivity value of 10 % to demonstrate the influence of this parameter on the derived temperature values. The results are briefly summarized in the table where P, r, and T denote shock pressure, reflectivity of shock front, and temperature, respectively.

P, GPa	T, K for r = 0 (band #1)	T, K for r = 0 (band #2)	T, K for r = 10% (band #1)	T, K for r = 10% (band #2)
4.6 ± 0.2	790 ± 20	797 ± 20	824 ± 20	838 ± 20
6.8 ± 0.5	1019 ± 30	1003 ± 30	1072 ± 30	1061 ± 30
8.1 ± 0.2	1125 ± 40	1090 ± 40	1187 ± 40	1156 ± 40
9.2 ± 0.3	1333 ± 20	1336 ± 20	1414 ± 20	1426 ± 20

Presented here data are in a fairly good agreement with experimental results obtained by other researchers in the visible range and with existing theoretical calculations.

REVIEW OF INVESTIGATIONS UNDER WAY ON THE LARGE-SCAL TSNIIMASH BALLISTIC FACILITY

Pavel V. Kryukov,

"Ballistic Technologies" Scientific Venture, Korolev, Moscow region, Russia

The large-scale TsNIIMASH ballistic facility was created in 1992 through modernization of large shock tunnel. Having 0.5-m caliber, the facility is 200 m long. In each experiment on the facility, stoichiometric hydrogen-oxygen mixture with a volume of up to 300 m3 is exploded, what is equivalent to an explosion of about 400-kg of TNT. In the air-evacuated ballistic channel, 60 m long, steel gyrostabilized plates, 0.5 m in diameter, are boosted by the action of the expanding products of detonating gas mixture and travel along the channel on a magnetic suspension without a mechanical contact with the channel walls. To date a technology has been developed for launching plates 6 mm thick, 9.1 kg weight, with the velocity of 3.5 km/sec, and plates 20 mm thick, 30 kg weight, with the velocity of up to 2 km/sec. The case is unique in combination of geometric dimensions of the ballistic facility with high-precise motion of the plate. In the foreseeable future we plan to increase the launch velocity of gyrostabilized plates weighing 9.1 kg to 5-6 km/sec.

The paper discusses the results of previously performed experiments on diamond dynamic synthesis through direct phase transition in graphite with no shock wave heating.

The paper also covers results of the work on the development of hypervelocity ballistic facility for launching compact aluminium projectiles, 2-4 g by mass, with the velocity of 14 km/sec. The hypervelocity ballistic facility is scheduled to be brought into operation in mid-1998. The working gas parameters desired for the hypervelocity launch are expected to be realized behind the front of the shock-wave which converges in the cone, 2.5 m long, butted against the end of the barrel, 0.5 m in diameter. We plan to boost compact projectiles of size 1 cm, keeping them intact, in the acceleration channel, 3.5 m long, within the barrel attached to the cone. A section of the facility, ca. 100 m long, together with the cone are filled with stoichiometric hydrogen-oxygen mixture so that the pressure does not exceed 10 atm. In the experiment the detonation wave propagates over the mixture, then transforms in the cone to a strong shock wave. Behind the shock-wave front, the gas density at the acceleration channel inlet reaches 50 kg/m3, while its velocity - 14 km/sec.

SHOCK WAVES GENERATION IN POROUS AEROGELS TARGET BY PULSE ELECTRON BEAM.

V.P.Efremov, V.E.Fortov, *B.A.Demidov, *I.A.Ivonin, ** N.Keeler

*HEDRC RAN, *RRC Kurchatov Institute, Moscow, Russia,*
***KAMAN Diversities Technologies Corporation, USA*

Interest to porous aerogel is determinated by perspective using of these materials as protector materials for cosmic apparatus from micrometeorits shocks. Also such materials are applied in targets for inertial confined fusion.

The purpose of this work is direct optical observation of energy deposition zone of pulse electron beam in condensed matter, measurements of expansion of porous dielectric material after fast volume heating and evaluation of equation of state

Shock waves in aerogel are generated by pulse electron beam. Relativistic electron beams are convenient for investigation of thermodynamic properties of matter under pulse volume energy deposition. Among their advantages, compared to laser and heavy ion beams, is a relatively large and good predictable range of electrons in a hot material. That makes the theoretical analysis of such experiments more simple. In this work the porous transparent dialectrical samples (SiO2) with densities 0.36, 0.24, 0.14 and 0.029g/cc were irradiated by the electron beam. The main advantages of aerogel targets compared to other materials are small density (large range of electrons) and the transparency of material. The transperence allows to measure the luminosity distribution along the energy deposition zone placing the recording device perpendicularly to the beam direction. The experiments were carried out on the KALMAR accelerator. The beam current was varied in the range 10-20 kA, the pulse duration was 80- 150 ns and the electron energy was from 270 keV to 290 keV. Absorbed energy distribution in the deposition zone has been compared with results of calculations made with and without accounting for hydrodynamic motion of the matter.

The samples of aerogel were cubic form. The beam diameter was about 10-12 mm. That ensures a plane exposition of the sample. The light luminosity from the energy deposition zone was recorded after passing through an optical system. That allows to measure velocities of expansion of aerogel in spite of electron beam direction and inside of materials. Besides we measured time of arriving disturbance from energy deposition zone to back free surface with laser interferometer.

These experimental data and one dimensional hydrodynamic simulations let us to test different equations of state. We used equation of state (Mie-Gruneisen) with elastic component taking into account self-matched change of

porosity under loading. This form equation of state gives more good agreement with all experimental data.

The work has been done due to financial support of the Russian Foundation for Basic Research (grant No. 97-02-16729).

METHODS OF STUDY OF NON - STATIONARY LOADS ACTIONON COMPOSITE CONSTRUCTIONS

Loborev V.M., Cheprunov A.A., Ostrik A.V., Petrovsky V.P.

Central Institute of Physics and Technology,
Russia, Moscow Region, Sergiev Posad

The paper examines experimental methods of study *of* composite constructions strength to the action of non-stationary loads and describes the complex, designed for study shock - wave actions on constructions. The complex contains the following elements:

• the set of explosive facilities designed for producing dynamic loads in the wide range of variable amplitude and spatial parameters:

• lest bench equipment for producing the stationary loads (shells heating, axial squeezing, internal pressure in bodies and their combination);

• facilities lo measure the load parameters and constructions response to mechanical loading.

With the help of the designed methods we've determined the relation between parameters of composite constructions response (models, fragments, working gas generators) and shock - wave load parameters. Also the paper discusses the new results of the experiments on the basis of those the processes leading to failure of composite constructions under shock - wave loading have been established.

STUDY OF SHOCK WAVES PRODUCED BY THE EXPLOSION IN MULTI - LAYER MATERIALS

Petrovsky V. P., Cheprunov A.A.

Central Institute of Physics and Technology,
Russia, Moscow Region, Sergiev Posad

The paper considers methodical questions of detection of wave process parameters in heterogeneous, multi - layer materials and presents the results of the experimental investigation of samples behavior linker pulse loading conditions. Shock waves were produced by way of sliding detonation of the elastic high - explosive. The tested samples comprised a multi - layer shield and the construction fragment.

The investigation involved determination *of* muss velocity and pressure

attenuation as the compression wave penetrates deep into the construction material.

The choice of the shield optimized for weight and damping properties was also made. The data obtained have been used to form the model of destructions and ensure the study of composite materials strength.

АНОМАЛЬНОЕ ПОВЕДЕНИЕ УДЕЛЬНОЙ ЭЛЕКТРОПРОВОДНОСТИ ВЫСОКООРИЕНТИРОВАННОГО ПИРОЛИТИЧЕСКОГО ГРАФИТА ПРИ МНОГОКРАТНОМ УДАРНОМ СЖАТИИ

В.И. Постнов, А.В. Уткин, В.Е.Фортов и В.В. Якушев

ИПХФ РАН

В работе представлены результаты исследования удельной электропроводности высокоориентированного (степень разориентации микроблоков 1^0) пиролитического графита при его превращении в алмазную модификацию в условиях многократного ударного сжатия в диапазоне давлений 10- 59 ГПа. В экспериментах использовали методику одновременного измерения удельного электросопротивления ρ образцов и регистрации профиля давления p с помощью манганиновых датчиков. Было зафиксировано увеличение ρ графита на 2-3 порядка при превышении давления фазового перехода пиролитического графита в алмаз $p_п$, равного примерно 20 ГПа. При этом оказалось, что 1- если амплитуда первой ударной волны p_1 режима многократного сжатия была больше, чем $p_п$, то время изменения сопротивления образцов, связанное с кинетикой фазового превращения, составляло 10-20 нс; 2- если p_1 было меньше $p_п$, тогда время возрастания сопротивления при фазовом переходе увеличивалось на 2 порядка. Вероятно это является результатом существенного нарушения исходной кристаллической структуры графита, приводящей к изменению характера превращения в данных условиях от мартенситного к диффузионному.

Неожиданными оказались результаты экспериментов, когда давление многократного сжатия превышало 48 ГПа. При этом давлении возникало необычное явление резкого уменьшения ρ образцов практически до исходной величины на фоне продолжающегося увеличения p.

С целью моделирования данного явления были проведено исследование поведения удельного электросопротивления композита: эпоксидная смола - мелкодисперсный графит при действии однократного ударного сжатия в диапазоне давлений 2-14 ГПа. Начальное ρ образцов составляло 10 МОм см и более в зависимости от объемного содержания графита (3-16)%. Такой исходный состав композита в определенной

степени имитировал состояние образцов пиролитического графита после полиморфного превращения. Было обнаружено, что сразу за фронтом ударной волны ρ композита уменьшается на 5-10 порядков, а сам переход имеет обратимый характер по мере прихода волны разгрузки. Замена в композите графита на мелкодисперсную окись алюминия привела к исчезновению явления.

Анализ полученных результатов показал, что переход исследуемых составов в проводящее состояние за фронтом ударной волны не связан с увеличением концентрации графита до уровня порога протекания. Причиной этому явлению могут быть неравновесные тепловые процессы, специфические для динамического сжатия гетерогенных сред с разной ударной сжимаемостью компонентов. По оценкам температура при этом на границах зерен наполнителя может достигать тысяч градусов, что должно привести к деструкции диэлектрической матрицы и появлению носителей тока. Таким образом тонкие разогретые слои диэлектрика могут играть роль проводящих перемычек между частицами проводящего наполнителя и являться основной причиной возникновения перколяции.

В заключение сделан вывод, что подобные процессы имеют место после фазового превращения пиролитический графит - алмаз и ответственны за аномальное поведение удельного электросопротивления исследуемых образцов в области 48 ГПа в режиме многократного сжатия.

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Z PINCH RADIATION SOURCES FOR HIGH PRESSURE EQUATION OF STATE AND CONSTITUTIVE PROPERTY MEASUREMENTS*

J.R. Asay, C.A. Hall, T.G. Trucano, T.A. Mehlhorn, C.H. Konrad, K.G. Holland

Sandia National Laboratories, Albuquerque, New Mexico, U.S.

Shock wave techniques have become a standard tool for studying the high pressure dynamic response of materials. An important advance in this field is the development of techniques for making detailed measurements of the time-resolved wave structure in shock compression and release waves. These techniques began with the development of stress wave gauges in the early 1960s and have evolved into a variety of high-resolution techniques that are being used in present shock physics applications. Traditionally, these techniques have been used with precision gun launchers and explosive loading techniques. Recently, we have demonstrated that Z pinch radiation sources can also be used to produce and diagnose shock wave profiles in materials at pressures exceeding 1 Mbar. The Z pinch technique developed at Sandia National Laboratories uses a cylindrically collapsing plasma produced through application of high current in an array of fine tungsten wires to produce intense x-radiation sources. The radiation produced through this process is contained in a gold coated container, referred to as a primary hohlraum, and subsequently used to ablatively heat a specimen in a secondary hohlraum. VISAR interferometry is used to measure the shock wave profiles produced in the specimen at varying propagation distances. Experiments performed on aluminum at shock pressures exceeding 1 Mbar demonstrate the use of this approach for studying a variety of radiation-hydrodynamic properties, including the ablation physics occurring during deposition of soft x-rays on a specimen and the high pressure thermophysical properties of the specimen, including Hugoniot response, isentropic loading, and mechanical properties such as high pressure material strength. In particular, it appears feasible to study the isentropic response of materials in condensed phases previously inaccessible in the laboratory with standard techniques such as plate impact or explosive loading. This presentation will discuss the Z pinch technology, recent results obtained on aluminum and other materials, and prospects for continued development of this technology.

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SESSION " Advances in Numerical Modeling Technology "

Co-Chairmen:

V.Kuropatenko - Russian Federal Nuclear Center, Chelyabinsk-70, Russia

I.Cameron - Atomic Weapon Establishment, Aldermaston, UK

THE CURRENT CODE STATUS IN MODELLING SHOCK PHYSICS PROBLEMS

I G Cameron

AWE, Aldermaston, Berks, England

The paper reviews the recent and immediate future developments in the application of hydrocodes to the solution of shock physics problems. Historically the greatest accuracy has been achieved by starting problems on a Lagrangian code and moving to an Eulerian one when mesh distortion becomes serious. This policy is reviewed in the light of modern developments. These include Arbitrary Lagrange Eulerian and Adaptive Mesh Refinement techniques in addition to meshless techniques such as the Smoothed Particle Hydrodynamic approach and the rapid evolution of computer hardware. The latter has been one of the most dramatic effects in hydrocode development in the current decade. The advantages of the various techniques are considered in relation to the many physical effects which have to be modelled in modern shock physics simulations.

TREK HYDROCODE FOR NUMERICAL SIMULATION OF 3D FLOWS OF MULTICOMPONENT MEDIUM

Yanilkin Yu.V., Tarasov V.I., Stadnik A.L., Bazhenov S.V., Bashurov V.V., Belyayev S.P., Bondarenko Yu.A., Gavrilova E.S., Gorev V.V., Dibirov O.A., Ivanova G.G., Kovalev N.P., Korol'kova T.V., Pevnaya P.I., Shanin A.A., Sofronov V.N., Toropova T.A.

RFNC-VNIIEF, Sarov (Arzamas-16)

The report is devoted to description of multi-purpose program complex TREK, intended to numerical simulation of 3D flows of multicomponent medium characterized by large deformations of interface boundaries.

The report considers the most general ideas and principles, laid into the groundwork for complex organization; discusses the methods for solving the problem of initial data calculation and visualization of calculation results.

The complex is intended for numerical simulation of gas-dynamic flows with regard to firmness of materials, diffusion processes, detonation of explosive substances, turbulent mixing and poly-disperse mediums' flows. Approximation for differential equations is produced in Eulerian or in Lagrangian-Eulerian variables. Concentration method is used for interface boundaries calculation, making possible to localize boundaries with an accuracy of one calculating cell. The brief description of calculating modules, implemented within the complex, is adduced.

There are presented the examples of simulation of several tasks by TREC cods: evolution of thin shell perturbations; impact penetration; rising up of explosive cloud; aerosols transport in atmosphere et al. The calculation results are compared with experimental data and with the results of calculations by the other methods. We have got a good agreement.

CALCULATIONAL TECHNIQUE FOR SHOCK WAVES WITH HEIGHTENED MONOTONICITY

I.R.Makeeva

Russian Federal Nuclear Center - VNIITF, Snezhinsk, Chelyabinsk region, Russia

In many difference techniques which are used to calculate shock waves quantities profiles in the vicinity of shock layer which substitute strong discontinuity are non-monotonic. In a number of techniques [1] non-monotonicity if conditional and oscillations amplitude could be minimized by selection of respective Courant number. Some techniques are absolutely non-monotonic [2] and some are absolutely monotonic [3]. The property of last one is that with decreasing Courant number the discontinuity is strongly "spreaded".

Oscillations and discontinuity "spreading " initially are calculational phenomena. Their effect on the processes taking place in a substance after shock passing have not been studied sufficiently. Behind the shock front various processes such as phase transfer, chemical reactions, destruction, etc. could be initiated in it. For a number of model problems quantitive effects of oscillations and profile "spreading" on evolution of mentioned processes is considered: the substance is "deceived" concerning the true conditions under which it is and its behavior is incorrect. The dependence of destruction point coordinates and new phase origin versus oscillation amplitude or gap "spreading" width.

To minimize mentioned effects the calculational technique for discontinue solutions of fluid dynamics is proposed in presented work; the property of profile monotonicity is combined with minimization of gap "spreading"

width. This effect is achieved by special form of difference equations and Hugoniot equations application for description of energy dissipation in the "spreading" zone. The results of calculations of a number of standard problems (shock, rarefaction waves) are given.

SIMULATION OF STRESS RELAXATION IN SOLIDS

V.A. Bychenkov, L.V. Khardina

Russian Federal Nuclear Center, Chelyabinsk-70, Russia

A mathematical model and numerical Lagrangian method were developed to calculate non-stationary elastic-plastic flows taking into account stress relaxation kinetics. Relaxation processes of shear stress, tensile stress and pressure in the porous materials are considered in a uniform context. The simplest form of relaxation equation for stresses in a motionless system is proposed. Problems of numerical simulation are considered, calculation results are presented describing dynamic processes of plane wave front evolution in quartzite and steel, and showing porous iron compression as a function of time and pressure. The calculation results are compared with the experimental data.

THE DIFFERENCE SCHEME OF GODUNOV FOR SIMULATION OF POLYMORPHOUS PHASE TRANSITION UNDER SHOCK-WAVE LOADING OF SOLIDS

Demidov V.N.

Institute of Strength Physics and Materials Science, Siberian Branch of RAS, Tomsk, Russia

Polymorphous phase transitions proceeding in shock waves were discovered experimentally for many metals, minerals and rocks. These phenomena were studied the most extensively for iron and alloys on the its base. Therefore, iron is used as model material in this work.

Here the analysis of questions connecting with numerical modeling of polymorphous alpha <--> epsilon transition in iron is carried out at the shock wave loading and the correct difference scheme is suggested for modeling of this phenomenon. The model of two phase elastic plastic medium is used in one velocity and one temperature approximation. This approximation is enough well-grounded for solid phase conversions. Really, the intensity of the heat exchange between phases and the forces of adhesion interaction in solid bodies are high to an extent that we may neglect the mackroscopic displacement of phases relatively to each other and the lack of coincidence of its middle temperature. We may consider that values of temperatures and rates of phases are equal to each other. Naturally, we assume that hypothesis on local thermodynamic equilibrium is correct not only into lim-

its each phase, but for two phase medium as whole. To describe the alpha <--> epsilon phase transition we use the equation of kinetics according to hich the rate of ones depends exponentially on the difference between chemical potentials of phases, and temperature dependence of "reaction constant" follows the traditional Arrenius law.

The explicit uniform monotonous difference scheme of first step of accuracy is developed for presented medium model, that is analogous to gas dynamics scheme of Godunov S.K. The results of numerical modeling of problem on high rate collision of iron plates are offered, that illustrates the typical peculiarities of evolution of wave picture of flow with phase transitions. There are the transformation of shock wave to "two wave picture", stipulated by alpha <--> epsilon transition and the formation of shock waves of unloading in the region of inverse epsilon <--> alpha transition. The comparison of numerical results and known experimental dates is given.

ANALYTICAL AND NUMERICAL STUDIES OF ACCELERATED THIN LAYER INSTABILITY

Bakhrakh S.M., Simonov G.P.

RFNC-VNIIEF, Sarov (Arsamas-16) Russia

The Raleigh-Taylor instability (RTI) studies present a certain interest due to a number of significant and urgent issues comprising high-speed throwing, inertial thermonuclear fusion, construction stability, etc.

Using the main equations represented in Lagrangian variables new analytical solutions have been obtained for the problems of thin accelerated layer Raleigh-Taylor instability at the non-linear in the observer space process stage.

Analytical solutions have been obtained for a liquid layer and for elastic layer with two-dimensional and three- dimensional perturbations. The perturbation pre-history dependence has been studied both from the kinds of perturbation (perturbations of the middle surface, perturbations of the layer thickness and the perturbations in the initial layer velocities) and from nondimensional parameters determining the perturbation nature. Depending on the parameter values both exponentially growing and limited solutions exist.

The relationship between the perturbations growth increment and the critical acceleration has been obtained for a thin elastic layer and the bounds of solution limitedness have been defined. The relations determining the influence of srength on the perturbation growth, particularly, on the conditions of their limitedness have been obtained.

It was demonstrated that contrary to the liquid the elastic layer three-dimensional perturbations (with a sufficiently large shift module) grow no faster than the two-dimensional ones.

The cases of the perturbation pre-history have been studied both for the constant and for the pulse acceleration as well as for the case with a constant and pulse accelerations acting simultaneously.

The influence of the perturbation wave lengths in different directions on a growth increment have been studied in three-dimensional cases.

The analytical solutions obtained were verified by the solution of a complete system of conservation laws for compressed continuum. The analytical solutions coincide with the results of the same calculations for thin layer, both for liquid and elastic, rather well. It was demonstrated by means of numerical experiments that the thin layer perturbation growth regularities occur in a finite thickness layer and in compressed semispace of both liquid and elactic continuum.

The analitical solutions obtained allow to get a further insight into the instability nature and mechanisms and prove to be good tests for two-dimensional and three-dimensional numerical techniques for calculations of continuum flows.

THE DEVELOPMENT OF A 2D ALE HYDROCODE

I.MacDonald

AWE, Aldermaston, Reading, RG7 4PR, UK

AWE are developing a 3D Arbitrary Lagrangian Eulerian (ALE) hydrocode. The first stage has been to extend to 3D the Lagrangian algorithm from the AWE 2D ALE code CORVUS and to implement this as the prototype code PEGASUS. The algorithm employs explicitly integrated, trilinear isoparametric finite elements for the spatial discretisation and a predictor-corrector time step. The prototype code has been successfully applied to a wide range of test problems.

A significant effort has been made to increase the efficiency of the algorithm in terms of both CPU and memory usage. CPU savings are possible by assuming the mesh to be made up of regions of logically rectangular mesh. The use of 1-pt quadrature as opposed to explicit integration has been evaluated with the conclusion that the reduction in CPU time is not sufficient to justify the resulting degradation in solution quality. Preliminary work has been carried out on mesh adaptivity as a precursor to a full ALE capability. This paper describes the current status of the code and presents recent results for some high explosive driven systems.

SESSION "Technical and Industrial Applications of Shock Wave Phenomena"

Co-Chairmen:
V.Titov - Institute of Hydrodynamics, Novosibirsk, Russia
W.Nellis - Lawrence Livermore National Laboratory, Livermore, USA

NUMERICAL SIMULATION AND REGULARITIES DETERMINATION OF SHAPED CHARGE METAL JETS DEFORMATION AND BREAK-UP

A.V.Babkin, S.V.Ladov, S.V.Fedorov, V.M.Marinin*

*Bauman Moscow State Technical University, *Scientific-Research Institute of Steel, Moscow, Russia*

Results of experimental and calculated theoretical investigations of explosively formed metal jet stretching are presented. Experimental study has been made by spark X-ray examination, calculations have been performed by means of numerical modeling based on mechanics of continuum.

Appearance of anomaly high metal plasticity in case of jet deformation and three jet failure types existence volume (led, tungsten), quasi-brittle (steel), plastic (copper, nickel, niobium, pure aluminum) have been noted. For the plastically breaking jets the presence of two typical stages has been noted: the first uniform deformation stage, when jet elements are holding near-cylindrical shape (inertia stage), and the second necking stage accompanied by the formation of many necks on the jet and resulted in jet break-up into separate non-gradient elements, when necks reach null radius. For estimating the stretching and break-up processes the coefficients of inertia extension n_i and limit elongation n_{lim} have been introduced. The other one separate elements quantity N resulted from the break-up and its connected relative initial length value $\bar{a}_0$ of jet part formed single element after break-up.

A number of physical-mathematical models of different complexity levels and appropriate results are presented. They describe the elements as an axially symmetric rods stretching at the constant axial velocity difference.

When analyzing shaped charge jet element as a cylindrical non-compressible plastic rod the character of kinematic, dynamic parameters and energy balance of stretching element has been established. Determination range of limit elongation n_{lim} has been found: lower bound from the hypothesis of jet material stay under the compression conditions in all directions, upper bound from the energy reasons.

When analyzing jet element as a cylindrical compressible elastic-plastic rod the existence of oscillation process has been found, which hasn't been discussed in the classical shaped charge theory. Dependence of oscillating process on jet parameters and its material characteristics have been revealed, conditions of oscillation growth and attenuation have been determined.

The main calculation data have been obtained when analyzing jet element as an compressible elastic-plastic rod of varying section and studying surface disturbances evaluation during the stretching process with the plastic break-up modeling. In this case the HEMP method have been used with the computational grid rezoning, extended lagrangian code opportunities to large deformations. Thus necking stage development features have been revealed, dealing with the axial velocity redistribution, deformation localization in neck and non-gradient parts formation. An approach to determination of the quantitative jet stretching and break-up characteristics n_i, $n_{lim.}$ $\overline{a}_0(N)$ is presented. The above characteristics dependencies of power type on jet parameters and material properties (united by a dimensionless complex characterizing inertia and plastic forces ratio) have resulted from calculation data approximation being in a good agreement with the available test results.

Possible explanations for remarkably regular character of relations calculated by a numerical model are presented. The reason has to do with dissipating energy minimum principle during jet deformation, which determines the transition from inertia to necking stage and controls separate element formation of certain size, emerging in form of "critical mass velocity concept".

In conclusion there are physical explanations for possible reasons of shaped charge jet behavior deviation for certain material from regularities typical for plastically breaking jets.

INVESTIGATION OF SHEARING IN CONTRARY WAVES DURING THE HIGH-VELOCITY PENETRATION PROCESSES

A.K. Divakov, V.A. Ermolaev, N.I. Zhigacheva, Yu.I. Mescheryakov, Yu.A. Petrov, C.A.Petrochenkov, M.V. Cil'nikov

Institute of the Mechanical Engineering Problems RAS, Special Materials Ltd, Saint-Peterburg

The main difficulty in studying the penetration processes is known to be a limited possibility for measuring the force and deformation characteristics of dynamic response of target. As a rule, the only what one can measure is the impactor velocity. By using the pulse X-ray technique it is also possible to measure a velocity of boundary between projectile head and non-disturbed region of target. However, space and temporal resolution in such a kind of experiments is insufficient to study an initial stage of penetration process.

At the same time, investigations of dynamic plasticity and strength in the uniaxial strain and spallation processes, which are based on the interference measurement of the free surface velocity of plane target, allow a detail information on both average free surface velocity profiles and micostructure kinetics at the mesolevel to be inferred [1,2].

In this relation it seems to be attractive to develop such schemes of dynamic loading of plane target when, on the one hand side, the plug formation in the target would occur and, on the another hand side, it would be possible to use the diagnostic techniques used during the uniaxial strain and spallation investigations. In this way in the presented work we propose a step-like geometry of the free surface of target, when conditions for redoubling the shear strain rate compared to commonly used elongated rod projectile are realized. In this case the shear failure begins from the free surface of target, which allows the initial stage of penetration process to be studied.

Shock tests and microstructure investigations has been directed on giving a work-out to the optimal scheme of plug formation during the plane collision of impactor and target. One of important, if basic, criterions of similarity of processes realized with commonly used technique of plug formation by using elongated projectile and that suggested in this work (shear in the contrary waves on edge of step) is thought to be the similarity of microstructure processes flowing in the shear zone in both cases. Microstructure investigations of fracture zone patterns show that geometry of fracture depends on the anisotropy of material very much. So, for the isotropic aluminum alloy D-16 plug formation is realized just on the edge of free surface step. As for Ц-85 armor steel the shear zone has a step-like shape. Longitudinal shear crack begins to propagate from the rear surface of target. Then on 2 mm depth it transits into crack of normal rupture parallel to the free surface of target. Such configuration is explained by the high shear strength of that material in comparison with spall-strength due to high unisotropy caused by rolling.

On the certain depth from the free surface energy of elastic-plastic wave turns out to be insufficient for shearing but sufficient for spallation. The situation reminds the well-known Ziner-Stro's mechanism for crack nucleation owing to dislocation pile-up.

The results of tests of both isotropic and unisotropic materials show that proposed technique for shear strain initiation allows to perform the shear deformation analogous that obtained during interaction of elongated impactor and plane target. At the same time, as distinct from the latter, plug formation performs under twice smaller impactor velocity. Technique allows the incubation stage of penetration process to be explored. Furthermore, the precise interference diagnostics used for studying the spallationcan be readily applied herein.

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INVESTIGATION INTO DEFORMATION OCCURRING AT SUPER DEEP PENETRATION OF POWDER PARTICLES INTO METAL MATRIX

Aleksentseva S. E., Krivchenko A.L.

Samara State Technical University, Samara, Russia

Treatment of metals by a high-speed particle flux formed by shock wave results in the effect of super deep particle penetration. With the speeds of shooting being 1.5 to 2 km per sec., the particles penetrate into a metal matrix to the depth of 1000 diameters of the particles with the critical diameter 100-140 micrometers, the collision pressure being 15 GPa and higher.

The metal as a dynamic system is in the state of stability before treatment. When a certain pressure is applied and the dynamic yield limit is overcome, the system is subject to irreversible changes. According to the second law of thermodynamics and the energy conservation law, the metal being deformed is a very nonequilibrium thermodynamic system in the state of plasticity. In this case, entropy indicates both the process reversibility and the measure of the disorder degree. When the dynamic yield limit is reached, the processes are irreversible due to changes in entropy.

The matrix material and the flow exchange both energy and matter, which is testified by the particles deeply penetrating into the material. Therefore, interaction of a directed flow of particles and metal matrix can be regarded as a common thermodynamic system.

The effect of the flux of high-speed particles causes the shock wave in the matrix material. At a certain characteristic pressure ($p1$), the material start to yield which is associated with fracture on the impact adiabatic curve.

Under the action of high-speed particle flux, stresses in Cu and Al matrices exceed the yield limit above which occurs irreversible plastic deformation.

The degree of deforming the metals considered in response to pulsing depending on the matrix volume V can be estimated by the formula $\varepsilon = 4/3 \ln V/V_0$. With a super deep particle penetration, the values of deformation are 16 -21 per cent.

The stress for a super deep particle penetration can be described by the following relationship $\sigma = p(1-2\nu)/(1-\nu)$, where p is pressure, ν is Puasson coefficient.

The characteristics of the deformed metal states and the change in entropy can be determined using approaches based on the rheological model of elastic-tough plastic body with linear strengthening, given in " Structuroobra-

zovaniye pri plasticheskoy deformatzii metallov ". Grigoryev A.K., Kolbasnikov N.G., Fomin S.G. This model describes the deformed metal with a continuous spectrum of relaxation times and yield limits τ.

The changes in statistical entropy from the initial state are based on the definition of entropy by Landau-Lifschitz $\Delta S = -R\int_{o}^{\tau} f(\tau)\ln f(\tau)d\tau$,

where R is the universal gas constant, $f(\tau)$ is the probability density characterizing the thermodynamic system state as a whole, and corresponding to transition to the irreversible state. The value of the nondimensional yield limit τ shows the energy state in a local area.

When the dynamic yield limit is reached, there starts the formation of new structural levels. This area contains the zone of super deep dynamic microalloying. A sudden slope of the entropy variation is consistent with and supported by a great number of experimental data on avalanche formation of dislocations under impact and the change of elastic stress field energies into surface energy of the newly-formed intergrain boundary. In response to pulsing, the atomic interaction energy changes. The frequency of atom jumps in the nucleus is higher than that in an equilibrium lattice, which corresponds to the increase in the diffusion coefficient.

The change in entropy can account for the reason why no super deep penetration occurs in case the matrix is bombarded with single particles, since when a metal matrix is bombarded by a single particle, its behavior corresponds to the area, where metal is in equilibrium state and has elastic stress field energy.

Thus, considering the critical conditions of a super deep penetration process, it has been found out that a metal matrix experiences, according to the value of strain, a complex of states and a change in thermodynamic potential. A super deep penetration is a system process of energy and matter exchange due to mature instability in the material caused by high-speed particle impact.

THERMODYNAMIC CALCULATION OF PHASE DIAGRAM OF SMALL CARBON CLUSTERS

S.B.Victorov, S.A.Gubin, I.V.Maklashova

Moscow State Engineering Physics Institute (Technical University), Russia

Condensed carbon in form of graphite or diamond nanoparticles is a major detonation product of many high explosives (HE). Small carbon clusters often present in combustion and explosion products of fuels and HE. Carbon nanoparticles are used as an initial material in some technological processes.

The regions of phase stability and synthesis conditions of carbon nanoparticles are little investigated. While the phase diagram of non-disperse carbon is well established even at high pressures and high temperatures, researches devoted to properties of small carbon clusters almost are not present.

At the same time the knowledge of carbon nanoparticles phase state and of their thermodynamic properties is important for understanding of processes proceeding at combustion, explosion and detonation, as well as for calculations of technological processes using these substances.

In this work it is supposed, that the sizes of crystals are not small so, that a qualitative state (internal structure) of substance has appreciably changed. Therefore, we consider that the structure, lattice parameters, bond energies and heat capacity of small clusters are equal to corresponding parameters of non-disperse crystals.

The distinction consists only of high surface energy of nanoparticles, that causes respective changes of enthalpy and entropy of substance. It is supposed, that the surface energy linearly depends on temperature and does not depend on pressure. Such assumption is convenient for carbon particles with number of atoms more than thousand and size above 10 nm.

Within the framework of offered model changes of enthalpy and entropy of crystal substance caused by its nanoparticle state do not depend on temperature and pressure, and are defined only by shape and size of crystals. Thus, the effect of structure and size of clusters on the thermodynamics of carbon particles can be described by correction of the standard-state heat of formation and entropy of carbon phases. The corrections to the heat of formation and entropy depend on shape and size of crystals.

We have obtained the equations of state (EOS) for non-disperse graphite, diamond and liquid phase of carbon with the Grüneisen gamma depending on specific volume only. All available experimental data on thermal expansion, heat capacity, shock-wave and static compression have been used to determine the best EOS parameters. These EOS have been applied to calculate a phase diagram of non-disperse carbon in a wide range of pressures and temperatures. The computed phase equilibrium lines and parameters of the triple points fit available experimental data and theoretical calculations.

The corrections for the standard-state heat of formation and entropy of carbon nanoparticles have been determined as dependencies on shape and size of crystals. To compute phase diagram of small carbon clusters we used the EOS obtained for non-disperse phases of carbon, and the chemical potentials for carbon nanoparticles were calculated with corresponding corrections for the heat of formation and entropy.

The phase diagrams of small carbon clusters have been computed for different shapes and sizes of the crystals. Each kind of carbon clusters (i.e. each shape and size of crystals) yields the own phase diagram. At given compact (a regular hexagonal prism) and thermodynamic favourable (an octahedron for diamond and a film for graphite) shapes of solid carbon crystals the pressure of graphite-diamond equilibrium grows at reduction of the size of particles.

Experimental data on synthesis of diamond nanoparticles by means of explosion also indicate to increase of the pressure of solid carbon phase coexistence with reduction of the crystal sizes. The sizes of carbon clusters affect to parameters of the graphite-diamond-liquid and the graphite-liquid-gas triple points: the pressure of phase coexistence increases, and the temperature decreases at reduction of the cluster size.

It was thus shown, that thermodynamic properties of nanoparticle differ from ones of the same non-disperse substance. The effect of crystal sizes causes displacement of phase equilibrium lines, change of melting temperature and of other characteristics of the substance. The offered model allows the use of known EOS and chemical potential of non-disperse substance to predict thermodynamic properties of nanoparticles of this substance.

STOCHASTIC MODEL FOR SHOCK-INDUCED GROWTH OF CRYSTAL MESOSYSTEMS IN THE CONDENSED ENVIRONMENTS

E.E. Lin

Russian Federal Nuclear Center - All-Russia Research Institute of Experimental Physics, Sarov (Arzamas-16), Russia

The report concerns a problem of growth of mesosystems in shock waves (SW) in the condensed environments containing crystal nanostructures. To describe such processes the author proposes stochastic model based on representations about phonon excitations of objects under consideration. The advanced earlier concept [1] of distribution density wave in space of the sizes of objects is applied to study the kinetics of shock-induced synthesis of crystals from nanostructures. The evolution of mean size $\langle a \rangle$ of object in time t is described by the self-similar laws, which define the bottom limit of complexity for macroscopic bodies achieved in a course of shock-induced growth of crystal mesosystems:

$$\rangle a\langle_{*} \approx \frac{18}{25}\left(\frac{4\pi}{3}\right)^{1/3} n^{-1/3} \exp\frac{E_w - E_0}{2kT}$$

Here n is the concentration of atoms in crystalline lattice, E_w, E_0 - energies of the nucleus of crystal structure in cluster volume and in the environment respectively, T - the environment temperature.

The received self-similar laws are applied to the description of synthesis of diamonds as in a detonation wave in solid high explosives, and in SW in porous medium consisting from carbon nanostructures.

We evaluate critical mean cluster size, starting from which nanodiamond can be considered as macroscopic particle, as $\langle a \rangle_* \sim 2 \cdot 10^{-9}$ m. Such cluster contains $\sim \left(\rangle a \langle_* / a_0 \right)^3 \approx 7^3$ nuclei (a_0 is the size of carbon framework of cyclohexan, which is considered as a nucleus of diamond structure), i.e. approximately 2000 carbons. The formation time for such particle has been evaluated as $t_* \sim 4 \cdot 10^{-10}$ s. We can conclude that the lower limit of complexity for macroscopic diamond-type particle has been reached already in the shock front in organic matter. We note that the above obtained evaluation for $\rangle a \langle_*$ coincides with the lowest fixed size of nanodiamonds, synthesized within detonation wave.

We deduce the following law of crystal growth in the course of its interactions with nanoclusters having crystalline lattices:

$$\rangle a \langle \approx \left(\frac{75 k \theta_D}{8 \pi A m_u n} \right)^{1/5} t^{2/5}$$

Here k, θ_D are Boltzman constant and Debye temperature of crystal respectively, A, m_u - atomic weigh and atomic unit of mass respectively. We deduce also the following law for growth of crystalline particles in the course of their vibrational interaction between each other:

$$\langle a \rangle \approx \left(\frac{27 k \theta_D}{2 \cdot 6^{1/3} \pi^{5/3} A m_u n^{4/3}} \right)^{1/6} t^{1/3}$$

On the basis of these expressions we describe the experiments on dynamic loading of porous samples from nanodiamonds and predict the conditions for making comparatively large diamond crystals in the metastable environment.

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RESEARCH OF THERMODYNAMIC PROPERTIES OF DETONATED NANODIAMONDS AND POWDERS, RECEIVED BY THEIR DYNAMIC COMPACTING.

A.N. Malyshev, E.E. Lin, S.A. Novikov, M.A. Pavlovskaya, V.I. Sukharenko, *K.B.Zhogova, * B.V. Lebedev

*Russian federal nuclear centre - All-Russia research institute of experimental physics, Sarov, *Research institute of chemistry in Nizhniy Novgorod state university, Nizhni Novgorod, Russia*

The element structure of a crystal lattice and thermodynamic properties of detonated nanodiamonds with the sizes from $2 \cdot 10^{-9}$ m up to $2 \cdot 10^{-8}$ m, received in [1], and also powders with the average size of particles ~ 10^{-6} m and ~ 10^{-5} m, received are researched by dynamic nanodiamonds compacting on a way [2]. The element structure of a lattice, determined with the help of the element-organical analysis has made: C [86,91 %], N [1,92 %], H [0,78 %], O [9,2 %], that corresponds to the data [3]. The specific heat of researched materials is determined by a method of adiobatic vacuum calorimeter in a range of temperatures from 100 up to 300 K. The experimental data of specific heat, and also the data on percentage in a lattice of atoms of carbon, nitrogen, hydrogen and oxygen, are used for account of thermodynamic functions: enthalpy of heat, entropy and Gibbs function. The received data of thermodynamic potentials are compared to the tabulared data for natural diamond (Fig.1).

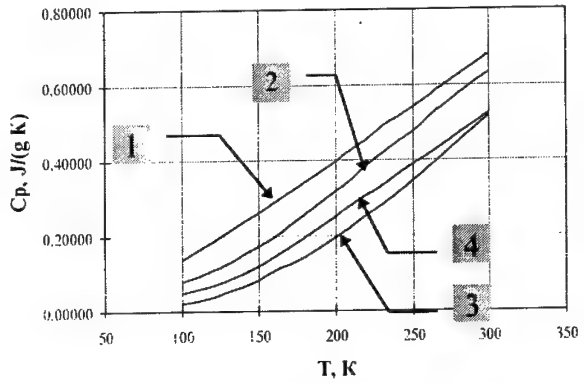

Fig.1. Specific heat:

1 - Graphite;
2 - Micropowder with the average size of a particle ~ $1{,}8 \cdot 10^{-5}$ м;
3 - Detonated nanodiamonds;
4 - Natural diamond.

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INVESTIGATIONS OF PROPERTIES OF SEMICONDUCTOR MATERIALS FROM NANODIAMONDS

E.E. Lin, S.A. Novikov, V.I. Sukharenko, A. I. Vasilieva, *V.D. Blank, *G.A. Dubitskii, **K.B. Zhogova, **B.V. Lebedev

*Russian federal nuclear center - All-Russia research institute of experimental physics, Sarov, *Federal scientific and technical center " Superhard materials ", Troitsk, Moscow region, **Research institute of chemistry in Nizhni Novgorod State University, Nizhni Novgorod, Russia*

The paper presents results of investigations of crystal structure, electrical, thermal, optical, and also mechanical properties of semiconductor materials from nanodiamons influenced by high dynamic and static pressures with the help of methods [1,2]. Electron diffraction patterns of nanodiamonds, doped in a detonation wave by electrical active impurities, testify to structural changes in a crystal lattice. Composition of doping impurities is determined on the data of mass-spectroscopy. The obtained mass-spectra of doped nanodiamonds show presence of impurity either from boron or from lithium. The optical characteristics of researched materials, in particular, absorption edge, are studied by method of Raman spectroscopy. Specific heats of doped and undoped nanodiamonds, determined by the method of adiabatic vacuum calorimetry, are compared with the data for natural diamond. It has been established that in temperature range from 100 K to 300 K the specific heat of doped sample differs from specific heat both of undoped one and of natural diamond. The temperature dependence of electrical resistance of samples in the range $T = 298 \div 873$ K shows that the energy E_a of conductivity activation of researched compounds corresponds to the well-known data for doped diamonds. Thus, the sample, doped by boron and aluminium simultaneously, has the value $E_a \approx 0.14$ eV at temperatures from 373 K to 873 K. Under subsequent cooling of the sample the activation energy increases approximately by factor of 2 in the range $T = 873 \div 523$ K and then decreases by jump up to 0.18 eV in the range $T = 523 \div 373$ K. The hardness and mechanical durability of

semiconductor compact samples correspond to the data for technical diamonds.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ХИМИЧЕСКОГО ВЗАИМОДЕЙСТВИЯ ПРИ УДАРНОМ СЖАТИИ В СИСТЕМАХ С ГАЗООБРАЗОВАНИЕМ.

А.В. Ананьин, О.Н. Бреусов, В.Н. Дробышев, С.А. Колдунов, В.Ф.Таций

Институт проблем химической физики РАН, п.Черноголовка Московской обл

Для химии ударных волн особый интерес могут вызывать объекты, результатом ударного сжатия которых является экзотермическое превращение с газообразованием, т.е. превращение, сопровождающееся заметным (конечным) изменением объема. В работе исследовалась возможность химического взаимодействия в смеси хлорида аммония и нитрита натрия в условиях, непосредственно реализуемых за фронтом ударного сжатия. Предварительно было изучено поведение этой системы в процессе нагревания при атмосферном давлении методами микро-ДТА и рентгенофазового анализа. Показано, что реакция может протекать в зависимости от скорости нагревания как жидкофазным путем, так и газофазным с образованием непрерывно разлагающегося нитрита аммония. Конечными продуктами реакции являются хлорид натрия, газообразный азот и вода. Протекание реакции существенно зависит от стехиометричности смеси, размера частиц, способа смешения и влажности исходных компонентов. Это принималось во внимание при подготовке образцов, проведении и анализе результатов газодинамического эксперимента.

В качестве основного метода исследований был использован метод торможения границы раздела (ТГР). Суть метода ТГР состоит в регистрации электромагнитным датчиком торможения границы раздела инертное вещество - исследуемое вещество, обусловленного превращением (энерговыделением) в слое ударно-сжатого вещества, непосредственно примыкающего к этой границе. Осциллограмма дает возможность определить момент начала этого торможения после входа фронта ударной волны и изменение его во времени, определяемое отклонением профиля движения границы раздела от заданного исходным воздействием прямоугольного, который регистрировался бы в инертной

среде. По амплитудам ударных волн охвачен диапазон давлений 0,9 - 10,8 ГПа. Время нахождения вещества в исходном ударно-сжатом состоянии и получения соответствующей информации достигало 5 мкс. Большая часть опытов выполнена с образцами из эквимолярной порошкообразной смеси с размером зерен не более 50 мкм при плотности 0.67 г/см3.

Газодинамический эффект, определенно свидетельствующий о химическом энерговыделении в изучаемой системе, наблюдался на нижней границе исследуемого диапазона. (Косвенным подтверждением энерговыделения за фронтом ударной волны являются также результаты наших экспериментов, в которых зарегистрирован меньший темп снижения параметров фронта в исследуемой химически активной среде по глубине по сравнению с распространением волны в инертном веществе).

При обсуждении полученных результатов представляется целесообразным провести сопоставления с некоторыми данными, известными для нитрата аммония (НА) как вещества, наиболее близкого к компонентам исследуемой смеси по химической природе, элементному составу, составу продуктов и энергетике превращения. В аналогичных условиях нагружения в НА протекает гораздо более интенсивное превращение. Это обстоятельство можно связать с двумя причинами. Во-первых, объем газообразных продуктов, отвечающий максимальному тепловыделению в НА, заметно больше. Во-вторых, существенным отличием является тот факт, что элементы, вступающие в реакцию с положительным тепловым эффектом, находятся в пределах одной молекулы. В этом случае диффузионные затруднения, имеющие, в принципе, тенденцию к возрастанию с давлением, сказываются в меньшей степени по сравнению с действием этого фактора при химических превращениях в механических смесях. Не исключено, что отсутствие заметного эффекта торможения в исследуемой смеси, ударно сжатой до давлений более 1.5 ГПа, связано именно с этими обстоятельствами. Выяснение этих вопросов требует дальнейших исследований.

Работа выполнена при поддержке Российского фонда фундаментальных исследований (грант № 96-03-34241а).

INVESTIGATION OF ROLE OF CONCENTRATION INHOMOGENEITY OF POWDER MIXTURE IN THE INITIATION OF "SHOCK-INDUCED" CHEMICAL REACTION

Leitsin V.N., Skripnyak V.A., Dmitrieva M.A.

Tomsk State University, Tomsk, Russia

The industrial application of technologies of synthesis intermetallic compounds with use of shock loading is restrained by weak study of base high-rate mechano-chemical processes. The research of these processes is possible with the help of computer simulation. Thus the adequacy to physical-mathematical model has essentially important meaning.

The main aim of the work is development of thermo-mechanical initiation model of chemical reactions under deformation of powders mixtures as Ti - Al, Ni - Al and etc.

Conditions of initiation of "shock-induced" chemical reactions are studied by the computer simulation method. It is assumed the pulse loading is applied to liquid phase before front of chemical reaction in porous powders mixture. In result this liquid phase penetrates deep into porous mixture, providing convective heat transfer and volumetric mode of chemical transformations. Simultaneously to it in powders mixture there is the plastic deformation of solid aluminium powder grains, at the expense of that a surface of interaction of reacting materials is increased. Temperature in the reacting layer is increased at the expense of plastic deformation energy and emission of heat at exothermic reactions of intermetallic compound synthesis. Mechanical loading provides non- diffusion transfer of components and products of reaction and acceleration of process of homogenisation.

The influence of concentration inhomogeneity of powder mixture on conditions of initiation and kinetics of chemical transformations is discussed in the frameworks of developed model. The concentration inhomogeneity is caused by local redundancy of the contents a component in relation to the average volume concentration and is caused by peculiarities of preparation of mixture.

It is considered the case, when these concentration inhomogeneity in macro-scale homogeneous mixture will form the spatial substructure. The parameters of spatial substructure define a mode of propagation of chemical transformation (stationary, pulsing, spin).

The mathematical model of chemical reactions initiation includes criterion, two-temperature equations of heat transfer and kinetic equation of chemical transformations. In the equations the heat transfer are taken into account the presence of heat sources, skeleton's heat transfer and volumetric convection heat exchange between a liquid phase and porous skeleton.

Computer simulation of processes, occurring in reacting layer at shock compression showed:1) The reaction of synthesis of intermetallic compounds in systems Ni-Al, Ti-Al can be initiated behind the front of shock wave and can be "self-assisted";2)The speed of propagation of front of chemical transformations is defined by a degree and parameters of spatial concentration inhomogeneity of powders mixture; 3) Necessary conditions for initiation of " shock-induced" chemical reactions includes the presence of non-zero porosity and certain initial temperature of a mixture. It is essential, that reduction of porosity and degree of concentration inhomogeneity of powder mixture can lead to changing of a mode of reaction and down to complete its prohibition.

INVESTIGATION OF PROCESSES OF MASS TRANSFER AND EXCITATION OF ELASTIC FLUCTUATIONS IN METALLIC PLATES UNDER THE LAZER HEATSTROKE.

Parkin A.A., Zhatkin S.S.

Samara State Technical University, Russia

Processes of intensive external influence on condensed media (lazer or beam influence, explosion, etc.) are of interest as they allow to study the conduct of the latter in a strongly non-equilibrium condition. Herewith a highly velocity heating or deformations in the system may cause such insufficiently studied processes as anomalous mass transfer, generation of shock waves and elastic fluctuations, influencing structural-phase conversions in the material and its performance characteristics. In the given work the influence of intensive heatstroke on mass transfer of alloying elements in metallic plates and excitation in them of elastic fluctuations under the pulsed lazer influence were investigated.

In these studies was used titanium alloy OT4-1M in the form of massive samples and fine plates 0.5 mm thick of different length, which were processed on lazer installation GOS-1001 with a pulse duration 1.4 ms in argon medium. Heating of material and deforming of the plates were checked by specially made optical pyrometers and vortex current sensor, which signals were written on the memory oscilloscope [1]. Before processing a plate was fastened cantilevered in a special frame, and its free unprocessed end was placed near vortex current sensor. Distribution of Al and Mn in samples in different depths of influence area was researched by the microanalyser "Superprob-733". Metallographic investigations were conducted on the transversal microscopic sections in the processing depth.

As a result of investigations it is established that after lazer processing a marked laminated structure with different contents of alloying elements in each layer is formed in the depth of a plate. Laminated structure is stipulated by the heating of each layer till the different temperature in the process of influence, as according to measurements the maximum value of the temperature

on the irradiated surface of the plate made 2300 K, while on the rear surface the temperature did not exceed 800 K. In distribution of alloying elements there was discovered their marked segregation with maximum of Al concentration in the melting area (MA) (2,48%) and maximum of Mn concentration at the rear surface of the plate (1,54 %) and their average values in unprocessed material 2,3 ± 0.03% and 1,35 ± 0,03% accordingly. In the area of thermal influence (ATI) there was noted the lowest total contents of the given elements. Besides, according to the data of the vortex current sensor, because of heatstroke in the plate there were intensive deformation processes, which caused its sagging relative to the sensor. At the same time, dynamic sagging maximum was observed at the moment of the heat front reaching the rear surface of the plate.

When processing the massive samples of the alloy OT4-1M similar redistribution of elements was not discovered. Joint analysis of processes of heating and deforming the plate, as well as absence of the given effect on massive samples points to the marked influence of intensive deformations on diffusion processes, running in it under laser radiation. Appearing in the process of external influence, voltages and deformations create concentration currents, causing the phenomenon of ascending diffusion, bringing about the secondary segregation, that is to inhomogeneous distribution of the components [2]. "Ascending" diffusion and removing the voltages under intensive deforming occurs quicker, than usual diffusion under the same temperatures.

In a number of cases intensive deforming of the plate under the lazer heatstroke was accompanied by excitation in it of elastic fluctuations, registered by the vortex current sensor, which frequency fell with the increase of the length of the plate, and their amplitude increased with the growing of intensity of influence. Herewith it was ascertained that fluctuations were aroused in the period of the most dynamic sagging of the plate and had a thermoelastic nature.

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ALUMINUM FORMING BY LOW DENSE EMULSION EXPLOSIVES

J. Campos, I. Plaksin, J. Gois, J. Ribeiro, R. Mendes and D. Pinheiro,

Detonics, Mechanical Eng. Department

Fac. of Sciences and Technology, University of Coimbra, 3030 COIMBRA, Portugal

Many studies show the main influence of ductility and toughness of metals in explosive forming. The elongation, measured by axial testing, must not be exceeded during explosive forming or the part will fail. This criteria shows aluminium and cooper to be the most adaptive materials.

The ideal explosive forming system must combine simplicity and low cost of operations without changing of formed material structure or without needing any supplementary thermal operation of treatment. The dieless forming has been chosen, with aluminum forming in open die with water as explosive media for shock transmission between the explosive and metal plate. The analysis of final shapes in free forming gives the influence of stand-off distance in this process, but needs special hold down rings and clamps to fix the formed plates. A previous work shows limits of this kind of forming. In order to avoid any ring or clamp it has been chosen to study a cylindrical configuration, with a cylindrical explosive charge in axis, with a diameter of 25 mm and an aluminium tube of diameters between 60 mm and 100 mm. The media between the explosive and the aluminium tube is always water.

The selected explosive is an emulsion aqueous solution, 10% (in mass) of water, of ammonium and sodium nitrates, respectively 72 and 10%, emulsified with oils, wax and emulsifiers, 5.5%, with hollow glass spheres (GMB) as sensitise, from to 2.5%, with an initial density 1170 kg/m^3, until 21%, with initial density of 970 kg/m^3. Theoretical predictions of detonation velocity D_{cj} and pressure P_{CJ} were performed using THOR code, with three different equations of state BKW, H9 and H1, assuming a Chapman-Jouguet model of detonation and a thermodynamic equilibrium of solid and gas detonation products. Obtained results are in a good agreement with calculations of other predicting codes and show the non-ideal behaviour of this kind of explosive. Experimental values of detonation velocity and pressure, using a double resistive wire technique and shock induced polarisation method, show respectively 5340 m/s and 12 Gpa. Increasing GMB concentration, until 21%, reduces density until 970 kg/m3 and detonation velocity until 2900 m/s. This is the selected explosive to change shock impedance (obtained by density times detonation velocity) and measured tube deformation.

Aluminium deformation is also predicted using DYNA 3D code, allowing the visualisation of position and velocity, as a function of time. Correla-

tions to experimental results prove the validity of this technology and configuration.

TREATMENT OF METALS WITH THE STREEM OF HIGHSPEED - PARTICLES.

Kirsanov R.G., Krivchenko A.L., Isaev D.V.

Samara

The interaction of the street of particles, dispersed by the energy of explosion, with the target makes the cover of the particles. If the size of the particles is within the frame of 8-100 μm, and their speed – 1-3 km/s, some part of the particles may penetrate into the target to the depth of some centimeters. The phenomenon of superdeep penetration of particles may be effectively used for the volumetrical microalloying of metals, but the problem of distribution of the inculcated material to the depth of the targets is the least investigated.

The research work is dedicated to the investigation of the distribution of the alloy in the surface layers of the targets made of tool steel. The target were treated with the street of tungsten particles, dispersed by the explosive accelerator. We used tungsten powders of 8 -16 μm and 20 – 40 μm. The mass was constant. RDX (7 - 20 g/cm^3) and HMX (7 - 12 g/cm^3) were used as explosives.

The targets were formed as cylinders with the height of 30 mm and diameter - 18 - 20 mm. We investigated the distribution of the tungsten with the help of apparatus "Superprob - 733"; the diameter of the probe was 40 μm, step inside - 100 μm. The value of tungsten concentration on each level was deduced from the results of 6 points.

The results of the experiment witness that the layer of tungsten on the surface of the target with concentration c = 20 -32% is followed by the one, which finds no signs of tungsten at all. The thickness of this layer is about 200 μm. We failed to find the connection between the thickness the unalloyed zone and the size of the particles and the type of an explosive as well.

The absence of tungsten signs in the layer of 200 mkm witnesses that the mass of a moving particle on this section is unchangeable, what is conditioned by many factors. From the point of view of the results some of the models should be specified.

Consequently, the results of research work may be of great importance to the finding out of the process of superdeep penetration and practical application of the phenomenon for the treatment of metals.

MECANISM INVESTIGATION OF SUPER-DEEP PENETRATIONS.

Kirsanov R.G., Krivchenko A.L.

SAMARA

One of the new technology in volume metal microalloyingis the process by current of separate powder particles in size 8-100 mkm, speeded up the energy explosion till velosity 1-3 km/s (in this case the effect of super-deep penetration is realazed). In using this effect, the knowledge of this mecanism is important; that is why done work is devoted to this question.

For this reason the analysis of shock wave interactions and process kinetics is conducted, accompanying the effect of super-deep penetration. It is loked on in succession: product detonation interaction with powder; product detonation interaction, current of separate particles and material of particles with target.

It is show product detonation powder interaction results in particles accelaration till velosity 1000-3000 m/s; then the cone of explosion charge with height equal the product of charge radius on relationship speed to the volume speed in product detonation takes part; and the hitch of product detonation powder; the warming up of particles in interaction with detonation wave and supplementary temperature increasing for the contact with warmed up gases. The estimate of particles temperature for different metals has been done, taking part in the super-deep penetration process.

The product detonation interaction, current of separate particles and particles materials with target is divided 3 interaction:

1) The weak - current of product detonation with materials target;

2) The stronger - particles with target materials, pressure 10-13 GPa in the whole surface;

3) Locally strong - the particle with surfase target, influence zone is not about particle's diametre. In this case the pressure is 10^2 GPa.

It's shown these interactions are reflected on the structure of processing material.

SESSION "Molecular Dynamics in Study of Shock Wave Processes"

Co-Chairmen:
P.J.Haskins - Defence Research Agency, Fort Halstead, UK
Ph.Simonetti - Commissariat a l'Energie Atomique/Center du Ripault, France

MODIFICATION OF THE MONTE-CARLO METHOD FOR SIMULATION OF THE PROCESSES IN SHOCK WAVES

A.L. Biryukov L.V. Katkovsky, *

Institute of Applied Physical Problems, Minsk, Belorus;
**Ministry of Defence, Moscow*

The Monte-Carlo (MC) method is widely used for numerical simulation of the physical processes in shock waves such as the calculations of the state equations, the partition and matter state functions, the phase transmissions, the collision and chemical reaction rates, the radiation transfer and etc. The calculations of the thermodynamic parameters and their distributions along the axes perpendicular to the shock wave front are practically always reduced to the problem of the computations of the multiple integrals or the various functionals defined by a Fredholm equation of the 2-nd kind. The various variants of quota sampling in the MC method are often used as the way of improving the computational efficiency both for the multiple integrals [1,2] and for the integral equations [3,4]. In this work the new versions of a quota sampling are proposed and some new quota (group) distributions applicable to the integrals and the integral equations are studied. In the case of the integral equations breaking up into groups is performed in the all possible trajectory space, Ω.

For the calculation of the integral $F = \int_{\Omega} F(x)dx$ over a multidimensional region Ω let us define the normalized probability density $p(x)$ for the distribution of the random points in Ω. Let the simple MC method estimate (without breaking up into groups) $\xi = F(x)/p(x)$ has the value of the variance $D_N\xi$ [1,2], N - the number of the random points in Ω. If the region Ω is breaking up into M disjoint sets Λ_α, let the variance of the corresponding

estimate $\bar{\xi} = p_\alpha F(x)/p(x), \quad (x \in \Lambda_\alpha)$, be $D_N\bar{\xi}$, where $\sum_{\alpha=1}^{M} N_\alpha = N$, $p_\alpha = \int_{\Lambda_\alpha} p(x)dx$. It is well known, that $D_N\bar{\xi} \le D_N\xi$, if $N_\alpha/N = p_\alpha \equiv \pi_\alpha^{(1)}$. We have proved that the point distribution $\pi_\alpha^{(1)}$ is a particular case of more general one that leads to the decrease of the variance of quota sampling:

$$N_\alpha/N = p_\alpha^u \Phi_\alpha^v \Big/ \sum_{\alpha=1}^{M} p_\alpha^u \Phi_\alpha^v \equiv \pi_\alpha$$

for any $u \ge 0, \quad v \ge 0$, that satisfy the relation $u + v = 1$. Here $\Phi_\alpha = \int_{\Lambda_\alpha} F^2(x)/p(x)dx$. Some other distributions that decrease the quota sampling variance have been also found. For a given set $\{\Lambda_\alpha\}$ and $p(x)$ there is known the distribution N_α/N [1], that gives the absolute minimum of the variance $D_N\bar{\xi}$, but this distribution is very hard for practical realization. The advantage of any distribution can't be determined in advance as a rule. The efficiency of the MC calculations is influenced by the complexity and the accuracy of the computations of such values, as Φ_α and others, the possibility and simplicity of realization of the corresponding distributions. Eight various distributions were studied. We have shown that breaking up of Ω only into two groups for the integral gives the decrease of the variance (sometimes considerable) with respect to sampling without breaking up.

For the Fredholm integral equation of the 2-nd kind in a multidimensional phase volume V:

$$\varepsilon(x) = \int_V K(x',x)\varepsilon(x')dx' + \varphi(x)$$

and the dependent functional F represented by the convergent Neumann series:

$$F \equiv \int_V \varepsilon(x)f(x)dx = \sum_{n=0}^{\infty} \int_V \dots \int_V \varphi(x_0)K(x_0,x_1)\dots K(x_{n-1},x_n)f(x_n)dx_0\dots$$

the n-component trajectory a_n is defined as a set of multidimensional space points $a_n \equiv \{x_0, x_1, \dots, x_n\}$, n = 1,2,...; $x_i \in V$, i = 1,2,...,n. Let

the set of the all virtual trajectories be broken up into the finite or denumerable number of nonoverlapping subsets Λ_α: $F = \sum_\alpha F_\alpha$,

$$F_\alpha = \sum_{a_n \in \Lambda_\alpha} \varphi(x_0) K(x_0, x_1) \ldots K(x_{n-1}, x_n) f(x_n) \equiv \sum_{a_n \in \Lambda_\alpha} F(a_n),$$

and also the summation over a_n involves both the integration on phase space and summation on n. Considering, that the kernel of the integral equation $K(x',x)$ is characterized by the decrease scale, $l(x)$, depending on $|x - x'|$, (for example, for the integral equation of the radiation transfer, $l(x)$ - is the photon mean free path), that in the common case is a function of x, let us define the optical length (by analogy with the radiation transfer equation) τ_n of the n-component trajectory a_n by the following way:

$$\tau_n \equiv \tau(a_n) = \sum_{i=1}^{n} \left| \int_{x_{i-1}}^{x_i} dx / l(x) \right| \equiv \sum_{i=1}^{n} \tau(x_{i-1}, x_i)$$

where the integration is made along the ray $x_{i-1}x_i$. For breaking up of the set Ω into the finite number of M groups we specify the nonnegative numbers $\rho_0 \equiv 0, \rho_1, \ldots, \rho_{M-1}$, dividing half-open interval [0; ∞] on M parts, and assume, that $a_n \in \Lambda_\alpha$, if $\rho_{\alpha-1} \le \tau_n < \rho_\alpha$, $\alpha = 1,2,\ldots, M-1$, $a_n \in \Lambda_M$, if $\tau_n \ge \rho_{M-1}$. We give the definition of the trajectory of probability density, that guarantees belonging of a_n to Λ_α. The collision-like estimate has been constructed for breaking up of Ω into the groups Λ_α being described above. The method of the numerical realization of the various trajectories distributions over the groups has been proposed. It is based on the random walks between the states of the regular Markov chain, composed by the totality of all virtual trajectories. It was shown that the use of the quota sampling in the trajectory space depending on their "optical" length for solving integral equations improves the efficiency of MC calculations. The best results for the model radiation transfer equation and the great optical thickness of V were received for the case of the uniform trajectory distribution over groups. The accuracy was the order of magnitude better than without quoting. At that $\rho_\alpha - \rho_{\alpha-1}$ was approximately equal to the effective optical thickness of V, and the number of groups were $M \sim 2 \div 10$.

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MOLECULAR-DYNAMICS INVESTIGATION OF THE DESENSITIZATION OF DETONABLE MATERIAL

Betsy M. Rice, William Mattson, and Samuel F. Trevino,

U. S. Army Research Laboratory, APG MD 21005 USA

A molecular-dynamics investigation of the effects of a diluent on the detonation of a model crystalline explosive is presented. The diluent, a heavy material that cannot exothermally react with any species of the system, is inserted into the crystalline explosive in two ways. The first series of simulations investigates the attenuation of the energy of a detonation wave in a pure explosive after it encounters a small layer of crystalline diluent that has been inserted into the lattice of the pure explosive. After the shock wave has traversed the diluent layer, it reenters the pure explosive. Unsupported detonation is not reestablished unless the energy of the detonation wave exceeds a threshold value. The second series of simulations investigates detonation of solid solutions of different concentrations of the explosive and diluent. For both types of simulations, the key to reestablishing or reaching unsupported detonation is the attainment of a critical number density behind the shock front. Once this critical density is reached, the explosive molecules make a transition to an atomic phase. This is the first step in the reaction mechanism that leads to the heat release that sustains the detonation. The reactive fragments formed from the atomization of the heteronuclear reactants subsequently combine with new partners, with homonuclear product formation exothermally favored. The results of detonation of the explosive-diluent crystals are consistent with those presented in an earlier study on detonation of pure explosive

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DETONATION HUGONIOTS FROM MOLECULAR DYNAMICS SIMULATIONS

J. W. Mintmire, D. H. Robertson,* D. R. Swanson, and C. T. White

*Naval Research Laboratory, Washington, * Indiana University, Purdue University, Indianapolis, IN*

Processes at condensed-phase shock fronts can occur on such short time (sub-picosecond) and length (sub-nanometer) scales that they are ideal for classical molecular dynamics (MD) simulations[1-3] that follow individual atomic trajectories. Although starting from an atomic-scale description, MD simulations have also proven able to treat enough atoms for long enough times to describe continuum properties of planar shock waves in non-energetic materials[1] --including such complex hydrodynamic behavior as shock-wave splitting caused by a polymorphic phase transition[2]. Therefore, MD simulations hold great promise both for studying discrete shock-induced chemistry in energetic materials[3] and for directly relating this atomic-scale chemistry to the continuum properties of planar detonations successfully described by the hydrodynamic theory of compressive reactive flows[4]. A better understanding of the relationship between atomic-scale chemistry caused by shock waves and the continuum properties of condensed-phase detonations could aid in the design of safer, more reliable explosives.

MD simulations of chemically-sustained shock waves, however, require new many-body potentials capable of simultaneously following the dynamics of thousands of atoms in a rapidly changing environment, while including the possibility of exothermic chemical reactions proceeding along chemically reasonable reaction paths from cold solid-state reactants to hot gas-phase molecular products. In addition, for a molecular solid (which is typical of many energetic materials), these potentials must incorporate both the strong intramolecular forces that bind atoms into molecules and the weak intermolecular forces that bind molecules into solids. Over the last several years we have developed a model energetic diatomic molecular solid based on many-body potentials that have these key ingredients. Simulations establish that this model can support a chemically-sustained shock wave with properties that are intrinsic to the material and consistent with experimental results and the classic Zel'dovich, von-Neumann, and Doering (ZND) continuum theory of planar detonations[5]. Remarkably, we find that when a chemically sustained shock wave is achieved, near

steady-flow conditions are reached at 50 nm behind the shock front in as little as 15 ps.

Our previous studies of piston driven shock waves were limited to simulations of unreacting systems[2], but we have recently applied this method to a series of detonating systems as well. This technique allows the rear boundary condition behind the detonation front to be varied, and subsequently for significant averaging of the pertinent thermodynamic variables. These simulations provide a means to directly calculate the detonation Hugoniot without having to determine the equation of state of the system from the model potential. A series of model systems, which exhibit a dissociative phase transition to varying extent, was produced by modifying the range of the reactive many-body potential. The effect of this phase transition on the detonation Hugoniot, which is in good agreement with continuum theory[4], will be presented. These promising results demonstrate that MD simulations using reactive many-body potentials provide a powerful probe of the interplay between the continuum properties of shock waves and the atomic-scale chemistry they induce in condensed-phase detonations.

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CONTENT

SESSION " Detonation Physics of Energetic Materials"

SESSION " Advances in Numerical Modeling Technology "

SESSION "Technical and Industrial Applications of Shock Wave Phenomena"